Microwave Journal

eBook

Development and Test of New Automotive Radar Technologies

November 2019

SPONSORED BY Electro Rent

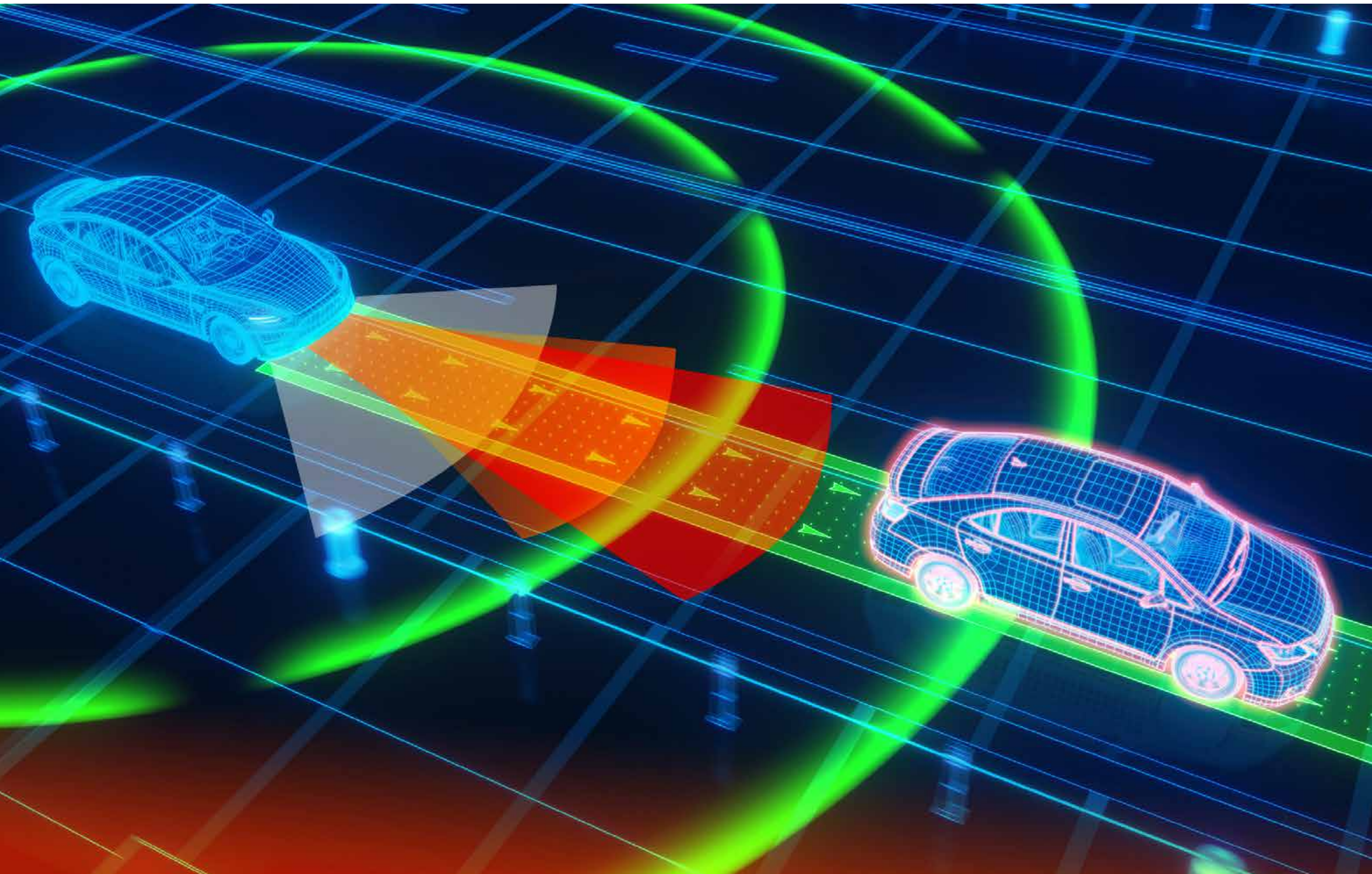


Table of Contents

Introduction

Development and Test of New Automotive Radar Technologies

Radar sensor technology has advanced rapidly in the last few years as highly integrated semiconductor technology has enabled lower cost, more advanced systems. This has allowed the technology to be applied to new markets like gesture sensing and health monitoring. Improved designs and better digital signal processing have greatly improved automotive radar sensor technology which is growing quickly to improve safety systems and enable the emerging autonomous vehicle market. According to MarketsandMarkets, the radar sensor market is projected to reach $20.64 billion by 2023, growing at a CAGR of 19.51% during 2017 to 2023.

This eBook includes articles about advanced radar sensor technology and methods for testing these products for design and development. MarketsandMarkets provides a market overview in the first article. In other articles, Uhnder reviews their new digital code modulation MIMO radar technology that improves automotive safety and then imec reviews their highly integrated 140 GHz FMCW radar for vital sign monitoring and gesture recognition applications. There are also several articles from test expert Rohde & Schwarz about measurement techniques for radar systems including optimizing beamforming from bits to RF beams, measurement of radar pulse stability and advanced methods for analyzing ultra-wide automotive radar signals.

This eBook is intended to help designers develop and test new radar sensor technologies as we have collected some of the latest articles in this area for this publication. Thanks to ElectroRent for sponsoring this eBook so that we can bring it to you for free. We hope that you gather some new design techniques or test methods from this eBook for your future work.

Pat Hindle, Microwave Journal *Editor*

Radar Sensors Market Overview

MarketsandMarkets

Radar systems are used to determine the presence, range, size, shape, and velocity of objects and can be classified as either imaging or non-imaging radar systems. Imaging radar systems create 2D images of target objects either through continuous wave signal or pulsed signal. The imaging radar system is prevalent in sectors such as industrial, agriculture, and healthcare, as well as environmental and weather monitoring applications. Non-imaging radar systems, also known as scatterometers, are used as speed gauges and radar altimeters.

A radar sensor, along with the transmitter, receiver, duplexer, and antenna, are important components of a radar system. Radar sensors help in determining parameters such as velocity, range, shape, and size of the target object by transmitting either continuous wave signal or pulsed wave signal. According to MarketsandMarkets, the *radar sensor market* is projected to reach USD 20.64 billion by 2023, growing at a CAGR of 19.51% during 2017–2023.

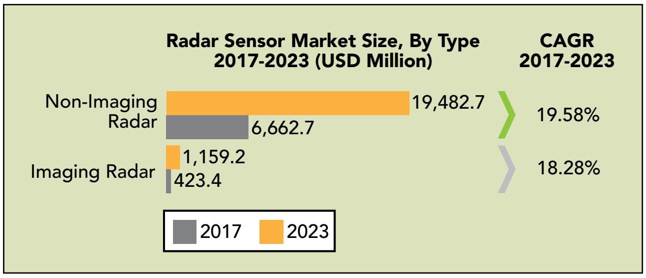
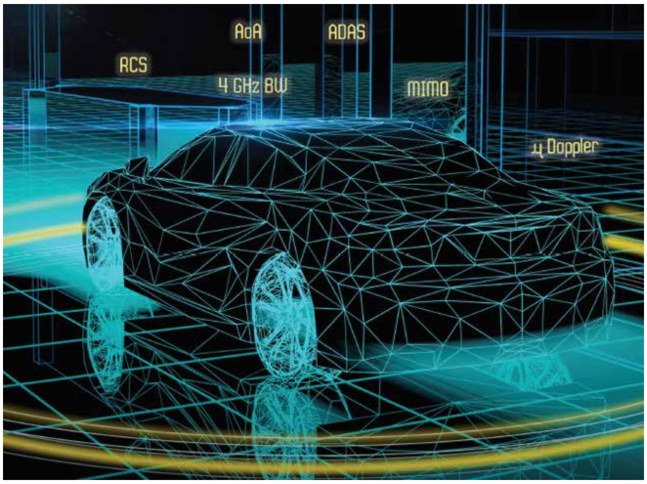


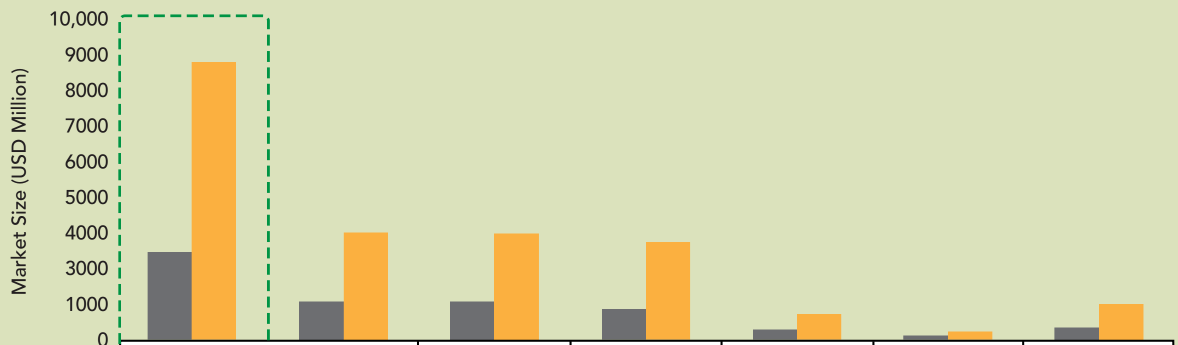
Fig. 1



CURRENT OUTLOOK

Radar systems are used in a wide-range of end-user applications, including automotive, aerospace, and military, as well as security & surveillance, traffic monitoring and management, environmental and weather monitoring.

In automotive, a radar system is used as adaptive cruise control and autonomous driving assistance systems (ADAS). In ADAS, radar systems are used for applications such as lane change support, collision avoidance, and parking aid, as well as pedestrian and cyclist detection, and step-&-go functionality. A short-range sensor in automobiles helps in collision warning, lane



	Automotive	Traffic Monitoring & Management	Environment AI & Weather Monitoring	Security & Surveillance	Industrial	Aerospace & Defense	Others
2017	2790.6	1253.4	1245.9	989.6	296.6	93.2	416.8
2023	8702.0	3412.3	3367.0	3079.5	795.8	145.3	1140.2
CAGR (2017-2023)	20.87%	18.17%	18.02%	20.83%	17.88%	767%	18.26%

Fig. 2

change assistant, blind spot monitoring, and parking aid, whereas a long-range radar system helps in identifying blind spots in front of the vehicle and in determining traffic situation ahead of the vehicle. According to MarketsandMarkets, the contribution of automotive is the highest in the radar sensor market and will continue to be dominant in the coming years.

The military/defense is another major segment in the radar sensors market. In the military, radar systems are used in missile control, ground surveillance, navigation, and military air traffic control, as well as to identify moving targets and assist in search and rescue operations. Increased military spending will lead to the growing adoption of radar sensors. According to the Stockholm International Peace Research Institute (SIPRI), global military spending increased by 2.6% in 2018 compared with 2017 in the US, China, India, France, and Saudi Arabia—top spenders that account for almost 60% of global military spending. Also, the increasing need for security and surveillance at borders has led to the requirement of advanced sensor network security system. This will propel the adoption of radar systems in the military/defense segment.

FUTURE OUTLOOK

Growing developments in the space of self-driving/autonomous vehicles are likely to drive the adoption of radars. Automobile companies, such as Ford, GM, Tesla, and Volvo, are planning to release driverless cars by 2021. For instance, Ford is planning to deploy almost 1,000 driverless cars by 2021, Volvo is planning to offer 100 Swedish customers early access to their autonomous XC90 SUV by 2021, and Tesla is planning to release self-driving taxis (robotaxis) by 2020 in the US. Therefore, the introduction of driverless cars is likely to propel the adoption of radar systems during the forecast period.

Developments have been observed in integrated radar technologies. For instance, in May 2019, a team of researchers from the Fraunhofer Institute for Laser Technology (Germany); the Fraunhofer Institute for Organic Electronics, Electron Beam, and Plasma Technology (Germany); and the Institute of High Frequency Technology at RWTH Aachen University (Germany) developed a process in which radar sensors can be coated on vehicle headlights. In May 2019, Libelium, a Spanish manufacturer of hardware and IoT solutions introduced a smart parking device for cars with integrated radar technology. Also, the continuous developments of military radar systems such as SPAR tiles from MACOM, Digital Array Row Transmitter (DART) from Lockheed Martin, and the Artisan 3-D radar system from BAE Systems help in the growth of the radar sensors market during the forecast period.

COMPETITIVE SCENARIO

Robert Bosch Gmbh, Lockheed Martin Corporation, Infineon Technologies AG, Continental AG, and HELLA GmbH & Co. KGaA are among the leading vendors in the market. Robert Bosch has gained popularity in the radar sensors market due to continuous investments in products related to automotive. For instance, in January 2019, Bosch announced to invest USD 1.1 billion to increase chip production owing to the rise in the adoption of sensors in cars. Apart from Robert Bosch, other vendors, such as Continental, HELLA, and Infineon Technologies, dominate the market due to their strong foothold in automotive. Lockheed Martin's dominance is attributed to its strong foothold in aerospace and defense. Autoliv Inc., BAE Systems plc, NXP Semiconductors N.V., Saab AB, and ZF Friedrichshafen AG are among the other major vendors in the radar sensors market.■

Phase Noise Analysis

Rohde & Schwarz FSWP26/B1/B4/B60

The R&S FSWP phase noise analyzer and VCO tester features very high sensitivity thanks to low-noise internal sources and cross-correlation. It can measure phase noise on highly stable sources such as those found in radar applications. Additional options such as pulsed signal measurements, additive phase noise (including pulsed) characterization, and integrated high end signal and spectrum analysis make the R&S FSWP unique.

Learn More

Key FSWP Facts

- Frequency range from 1 MHz to 8/26.5/50 GHz
- High sensitivity for phase noise measurements thanks to cross correlation and extremely low noise internal reference sources
- Typ. –172 dBc (1 Hz) at 1 GHz carrier frequency and 10 kHz offset
- Typ. –158 dBc (1 Hz) at 10 GHz carrier frequency and 10 kHz offset
- Simultaneous measurement of amplitude noise and phase noise
- Internal source for measuring additive phase noise, including on pulsed signals
- Signal and spectrum analyzer and phase noise analyzer in a single box
- Wide dynamic range thanks to low displayed average noise level (DANL) of –156 dBm (1 Hz) (without noise cancellation) and high TOI of typ. 25 dBm
- 320 MHz signal analysis bandwidth
- Total measurement uncertainty: < 0.2 dB up to 3.6 GHz,< 0.3 dB up to 8 GHz
- Touchscreen operation

ROHDE&SCHWARZ
Make ideas real

Microwave Signal Generation

Rohde & Schwarz SMA100B-20/HW4

The R&S SMA100B RF and microwave signal generator delivers maximum performance without compromise. It provides pure output signals while maintaining the highest output power level. It can handle the most demanding component, module and system measurement tasks in the RF semiconductor, wireless communications and aerospace and defense industries.

Learn More

Key SMA 100B Facts

- Frequency range from 8 kHz to 3 GHz, 6 GHz, 12.75 GHz or 20 GHz
- Excellent SSB phase noise of –152 dBc (typ.) at 1 GHz and

  –132 dBc (typ.) at 10 GHz, each at 20 kHz offset
- Virtually no wideband noise –162 dBc (meas.) at 10 GHz and an offset of 30 MHz
- Ultra-high output power
- Up to 38 dBm with the 6 GHz instrument
- Up to 32 dBm in the microwave frequency range with the 20 GHz instrument
- Exceptionally low harmonics
- State-of-the-art GUI with touchscreen

ROHDE&SCHWARZ
Make ideas real

Digital Code Modulation MIMO Radar Improves Automotive Safety

Vito Giannini, Manju Hegde and Curtis Davis
Uhnder, Austin, Texas

Automobiles are technologically sophisticated and connected. Newer vehicles include advanced sensor technologies to improve safety, and manufacturers continue to incorporate more sensors to provide real-time data from the external environment to the driver and the car's control systems. These sensors enable many safety features: early warning, corrective steering and braking systems encompassing lane departure, adaptive cruise control, autonomous emergency braking and blind-spot detection.

Nevertheless, new solutions are needed to increase safety and achieve truly autonomous driving—at level 5 of the Society of Automotive Engineers capability scale. Recent research and investment have targeted sensor technologies such as LiDAR and enhanced passive imaging, i.e., cameras. Some industry pundits have posted that autonomous driving vehicles will include a very rich portfolio of these optical sensors on the path to levels 4 and 5. Perhaps counterintuitively, radar, which has been a mainstay in vehicles for some years, has not achieved the same fanfare as LiDAR, since radar already offers a stable, all weather, cost-effective sensor to help enable the current levels of autonomy and safety. On the other hand, compared to optical technologies, one radar weakness is angular resolution, defined as the minimum angle the radar can distinguish and separate two equally large targets at the same range.

This article discusses the application of new technology and advanced signal processing that will enable radar to do much more. First, basic concepts about angular resolution and antenna patterns in radar will be described. Then, Uhnder's development of digital code modulation (DCM) radar with coherent MIMO technology will be discussed, outlining its advantages compared to state-of-the-art radar technology.

ANGULAR RESOLUTION

A radar's angular resolution is directly proportional to the effective area of its antenna array, typically referred to as the antenna aperture. As shown in ***Figure 1***, when defining angular resolution, the main lobe half-power points (−3 dB) of an antenna's radiation pattern are normally specified as the limits of the antenna's beamwidth. Two identical targets at the same distance are resolved in angle if they are separated by more than the −3 dB beamwidth. In the common driving scenario shown in Figure 1, to distinguish two identical cars at a slant range, R, from the sensor and spaced at distance, d,

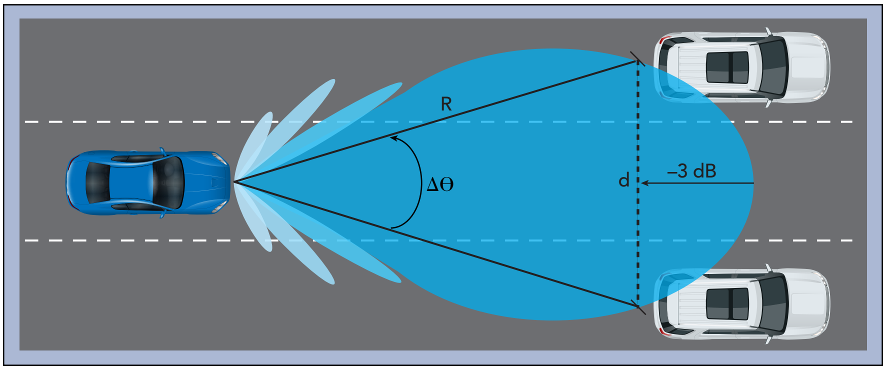


Fig. 1 The angular resolution of a radar is determined by the −3 dB beamwidth of the main lobe.

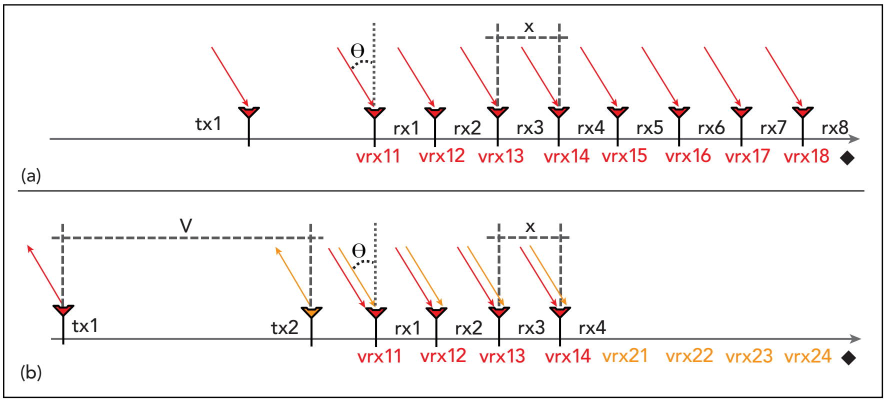


Fig. 2 Standard (a) and MIMO (b) antenna arrays to achieve eight virtual receivers.

from each other, the required angular resolution is defined by the following expression:

$$\Delta\theta = \sin^{-1}\left(\frac{d}{R}\right) \qquad (1)$$

For example, if d = 4 m and R = 125 m, an antenna beamwidth of 1.8 degrees is required to achieve this angular resolution. This case exemplifies the scenario where the vehicle needs to decide whether the lane between the two cars is occupied. It is a challenging requirement for currently deployed automotive radars, which achieve a few degrees of angular resolution at the expense of having a very narrow field of view (FOV) and ambiguity in angles (i.e., allowing targets from multiple angles to fold onto each other). Fortunately, that issue can be solved with a coherent MIMO radar.

MIMO RADAR

To understand the MIMO radar, refer to ***Figure 2a***, which shows the physical antenna configuration for a quasi-monostatic radar. A single transmit (Tx) and eight receive (Rx) antennas provide closely located channels, forming a single-input-multiple-output (SIMO) radar. The distance x between the Rx antennas is chosen to achieve the desired unambiguous FOV:

$$\pm\theta_{FOV} = \pm\sin^{-1}\left(\frac{\lambda}{2x}\right) \qquad (2)$$

where λ is the wavelength. This unambiguous FOV defines the angular region within which the target directions are uniquely identified, assuming all targets are within this region. Targets beyond this region will appear to fold into it and cannot be distinguished from the targets within the region. The FOV will be maximum (±90 degrees) when x = λ/2. That is the preferred choice to avoid ambiguities when estimating target directions. When Tx1 sends a waveform, the eight Rx antennas will receive an attenuated copy of the signal, shifted in phase by a constant Φ between each of the eight Rx antennas. The phase shift is computed from:

$$\phi = \frac{2x\cdot\pi\cdot\sin(\theta)}{\lambda} = \pi\cdot\sin(\theta)\,\text{if}\; x = \frac{\lambda}{2} \qquad (3)$$

where θ is the angle of arrival or the target's direction. From the receiving antenna Rx1 to Rx8, the total phase shift will be 7Φ.

A completely equivalent result can be achieved with a thin MIMO array, shown in ***Figure 2b***, which is formed with two Tx antennas separated by 2λ and four Rx antennas separated by λ/2. In this case, each Rx antenna will receive a pair of waveforms, Tx1 and Tx2. For the Rx channels to separate the signals coming from the two Tx antennas, the transmitters need to generate orthogonal waveforms. After matched filtering of the two Tx waveforms, to separate the received signals from the two transmitters at each receive antenna, eight virtual receivers (VRx) are created (i.e., 2 × 4 = 8), which have equivalent phase shifts as the configuration of Figure 2a.

The single and dual Tx configurations provide equivalent angular resolution. However, the MIMO architecture uses only six antennas, compared to nine with the SIMO design. The reduction in hardware with the MIMO version is a significant advantage.

This same principle, on an entirely different scale, was used in space research to create the first direct images of a black hole. Astronomers created a "virtual telescope," a planet-scale array comprising eight radio telescopes, to increase the antenna aperture and improve angular resolution down to 20 μarcseconds—3 million times sharper than 20/20 vision.[1]

An antenna array, like those in Figure 2, will have a beamwidth given by:

$$\Delta\theta = \frac{\lambda}{N_{Tx}\cdot N_{Rx}\cdot x\cdot\cos\theta} = \frac{2}{N_{Tx}\cdot N_{Rx}\cdot\cos\theta}\,\text{if}\; x = \frac{\lambda}{2} \qquad (4)$$

where N_{Tx} and N_{Rx} are the number of Tx and Rx antennas, respectively. Both arrays have an angular resolution of approximately 14 degrees. For comparison, ***Figure 3***

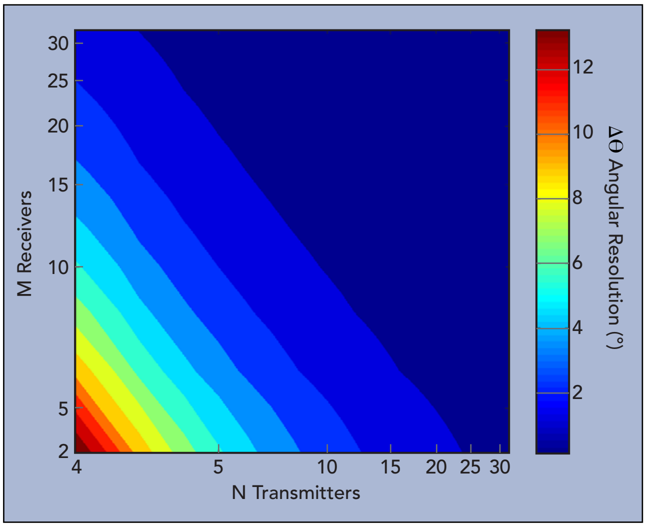


Fig. 3 Angular resolution for a MIMO radar vs. number of Rx and Tx channels.

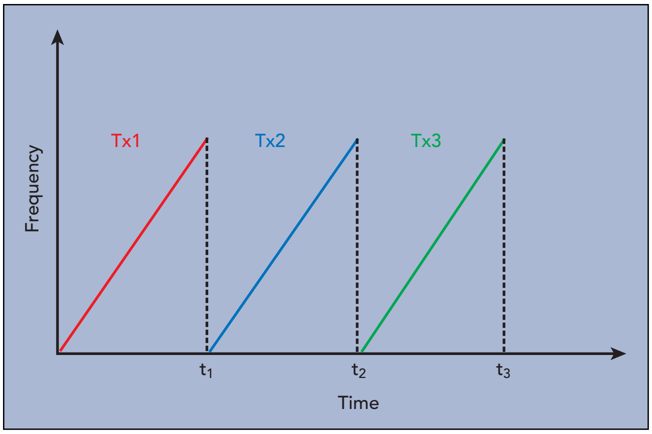


Fig. 4 Frequency vs. time for an FMCW radar.

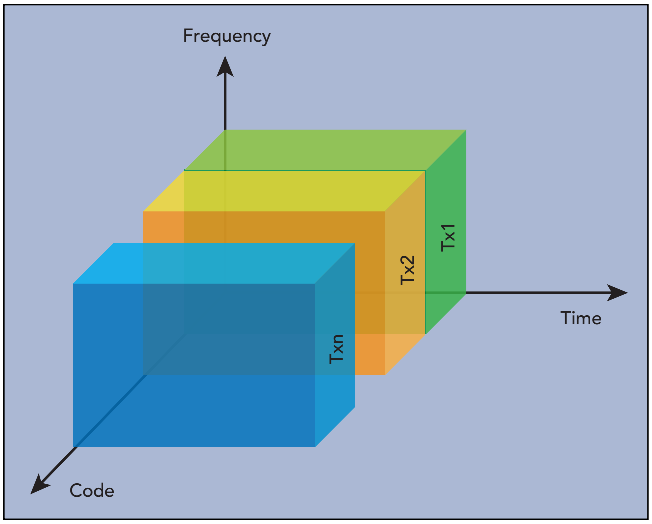


Fig. 5 Code domain MIMO.

shows the achievable angular resolution at boresight (θ = 0) versus the number of Rx and Tx antennas. From the figure, an angular resolution of 1.8 degrees can be achieved with a configuration combining eight Rx and eight Tx antennas.

MIMO + WAVEFORMS

As mentioned, Tx orthogonality is key to the Rx channels distinguishing the Tx signals. While there are multiple ways to achieve orthogonality, almost all have costly engineering trade-offs. The choice ultimately depends on the application and the radar waveform.

Frequency modulated continuous wave (FMCW) radars are by far the most popular for automotive. Numerous FMCW MIMO implementations have been reported, with the most common using a time-division multiplexing (TDM) approach. This is not true MIMO, although it can be a good approximation, as the signals are not a snapshot of the same environment, given the time delay. ***Figure 4*** shows how FMCW works with a three Tx radar sharing the same frequency modulated band. The radar frame is divided into three time slots, each devoted to one transmitter. The received signals are distinguished and processed based on this time division. One disadvantage of this option: since the transmitters are not operating at the same time, the maximum Tx output power is limited to the output from a single Tx. Consequently, while the FMCW TDM radar gains angular resolution, it trades maximum achievable range.

An alternative is where the transmitters share both frequency and time and are differentiated with orthogonal phase-coded waveforms (see ***Figure 5***). Each transmitter radiates a uniquely coded signal which is "matched" by the receiver. Transmitting on all Tx channels simultaneously provides a link budget gain of $10\log_{10}(N_{Tx})$. This can be used to increase the maximum range, without affecting other radar parameters, or to reduce the area of the silicon used for functional blocks like the power amplifiers.

Conceptually, DCM radars modulate the phase of the transmitted signal during a given time period, called the chip period or chip duration, where each phase is one of a finite number of possible phases. For simplicity, assume the modulation is binary phase shift keying (BPSK). The phase modulated signal is spread using a predefined code consisting of a sequence of chips and is mapped onto a sequence of phases to create the transmitted signal. The signal is of the form

$$s(t) = \sqrt{2P}\cos\left(2\pi f_c t + \phi(t)\right) \qquad (5)$$

where P is the power, f_c is the carrier frequency and $\Phi(t)$ is the phase of the transmitted signal. While the phase can vary continuously to minimize bandwidth, the phase function is a sequence of phases held constant for T_c seconds, where T_c is the chip duration. That is,

$$\phi(t) =$$
$$\phi_l \text{ for } l\,T_c < t \le (l+1)T_c, l = 0, 1, \ldots \qquad (6)$$

where a(t) is either +1 or −1, corresponding to $\Phi(t)$ = 0 or π, respectively.

The sequence of values of the binary modulation signal are called chips. The sequence of chips causes the spectrum of the signal to spread the energy over a bandwidth proportional to $1/T_c$.

The baseband spreading waveform, a(t), that modulates the oscillator to generate the transmitted phase modulated CW signal, s(t), is given by

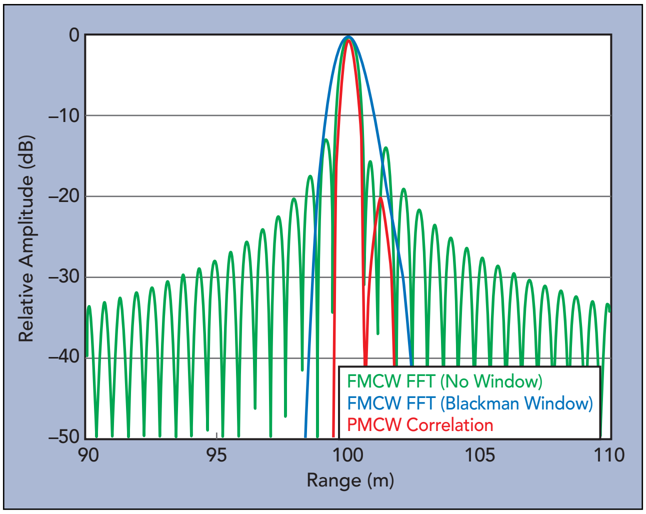
$$s(t) = \sqrt{2P}a(t)\cos(2\pi f_c t) \qquad (7)$$

where a(t) is either +1 or -1, corresponding to $\phi(t)$ = 0 or π, respectively.

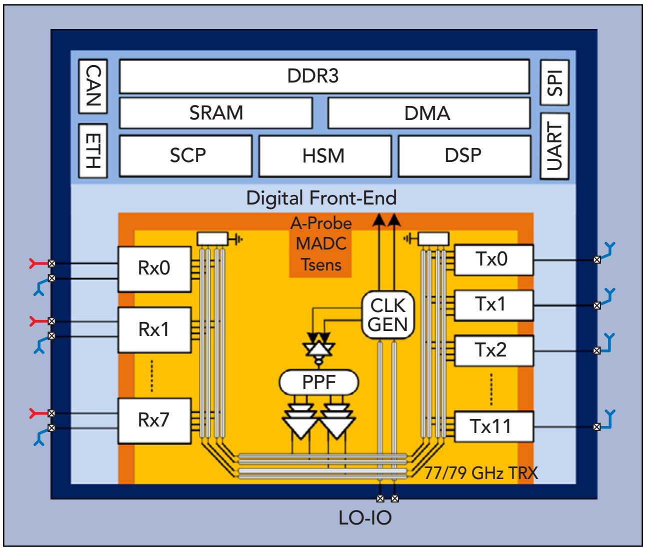
The transmitted signal from a single antenna is reflected off the targets in the environment, and the reflected signals at the receiving antenna are processed. A simple model for the received signal is

$$r(t) = \sum_{l=1}^{L} \alpha_l s(t - \tau_l) \qquad (8)$$

assuming L targets that reflect the transmitted signals. The transmitted signal, s(t), reflected by a target is attenuated by the factor α_l and delayed by τ_l between the transmitter, target and the receiver. The delay between the transmitted signal and the received signal is related



▲ **Fig. 6 Correlation of two targets with large differences in radar cross section.**



▲ **Fig. 7 Radar SoC, including 77 to 79 GHz MIMO transceiver with 12 Tx and 8 x 2 Rx, DSP, memory and interfaces.**

to the distance by $d_l = c\ \tau_l/2$, where c is the speed of light and the factor 2 reflects the roundtrip time from the transmitter to the receiver.

The digital signal processing includes a matched filter to determine the correlations of the received signal with various delays of the transmitted signal. In a DCM system, multiple periods of the spreading code are transmitted, and the matched filter produces an output at time t that corresponds to the correlation of the input from time t−T, where T is the duration of the matched filter's impulse response. The red curve in ***Figure 6*** shows the correlation between phase modulated signals that are reflected by two close targets, about 100 m distance and approximately 20 dB difference in radar cross section. The targets are easily distinguished, showing the capability of DCM systems to discriminate targets in challenging high contrast resolution scenarios. For comparison, the target discrimination of an FMCW radar are also plotted (see the green and blue curves), showing the FMCW returns limited somewhat by the windowing of the fast Fourier transform (FFT).

FIRST DIGITAL AUTO RoC

Uhnder has developed a radar sensor IC that incorporates advanced digital signal processing techniques, such as MIMO, to create a new generation of automotive radar sensors. This fully integrated radar on a chip (RoC) was designed for flexibility, a versatile platform to support diverse applications while minimizing cost.

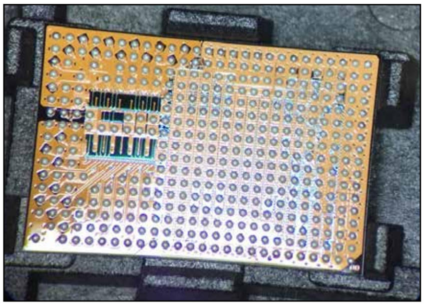
This RoC architecture is based on DCM with phase modulation and MIMO, capable of processing up to 192 virtual receive channels without external RF PCB circuitry. The RoC (see ***Figure 7***) integrates a 77 to 79 GHz transceiver with 12 Tx and 16 Rx channels that can be time-multiplexed to two sets of antennas, covering both azimuth and elevation profiles. The RoC uses a 15.2 to 16 GHz local oscillator (LO) generated by an external phase-locked loop, with differential LO inputs converted to quadrature using a polyphase filter.

The transmitter uses a Gaussian minimum shift keying (GMSK) digital modulator feeding a zero IF quadrature up-converter to mmWave. At baseband, a programmable pseudo-random noise (PRN) code is generated, digitally GMSK modulated and fed into current-steering 2, 4 and 8 GSPS digital-to-analog converters, whose current outputs are amplified and filtered by reconstruction filters.

Compared to BPSK implementations, this transmitter achieves higher spectral efficiency due to the absence of the large adjacent frequency sidelobes. The quadrature GMSK up-converter generates a constant envelope phase modulated signal, so it can use a fully saturated power amplifier to maximize efficiency while meeting the challenging link budget—a big challenge for all mmWave systems. Using DCM technology and MIMO enables the Uhnder design to place more power on target by simultaneously using multiple Tx channels with different codes. Transmit phased array is an available mode of operation that allows the user to trade field of view for higher effective isotropic radiated power. For a given link budget, designing smaller power amplifiers becomes a desirable and viable option.

At the receiver, the received signal is amplified with a low noise amplifier (LNA), mixed down to baseband using the same oscillator as used for the transmitter. Converted from analog to digital, the signal is digitally processed to estimate the range, frequency, Doppler and angles of the targets in the environment.

With Uhnder's implementation, the spreading code can be a PRN sequence with a very large period, so it appears to be a nearly random sequence. The resulting signal has a bandwidth that is proportional to the rate at which the phases change (i.e., the chip rate), which is the inverse of the chip duration. By comparing the return signal with the transmitted signal, the receiver can



▲ **Fig. 8 SoC in a fan-out wafer-level package.**

determine the range and the velocity of reflected targets.

The Rx front-end addresses the modulated self-interference artifact from the radar's internal transmitters, which can saturate the receiver and increase the correlation noise floor. This challenge is more significant in MIMO radars, where multiple Tx active channels may constructively sum up at specific Rx inputs. To address the self-interference artifact, the RoC cancels self-interference using a pattern generator unit combined with separate analog and digital interference cancellation units (A-ICU and D-ICU, respectively). The A-ICU runs a background channel estimation algorithm, continuously calculating the impulse response, including the signal path delays, and then applies corrections to the upconverted mmWave feedback signal, where the resulting signal is then power-combined into the transformer feeding the LNA.

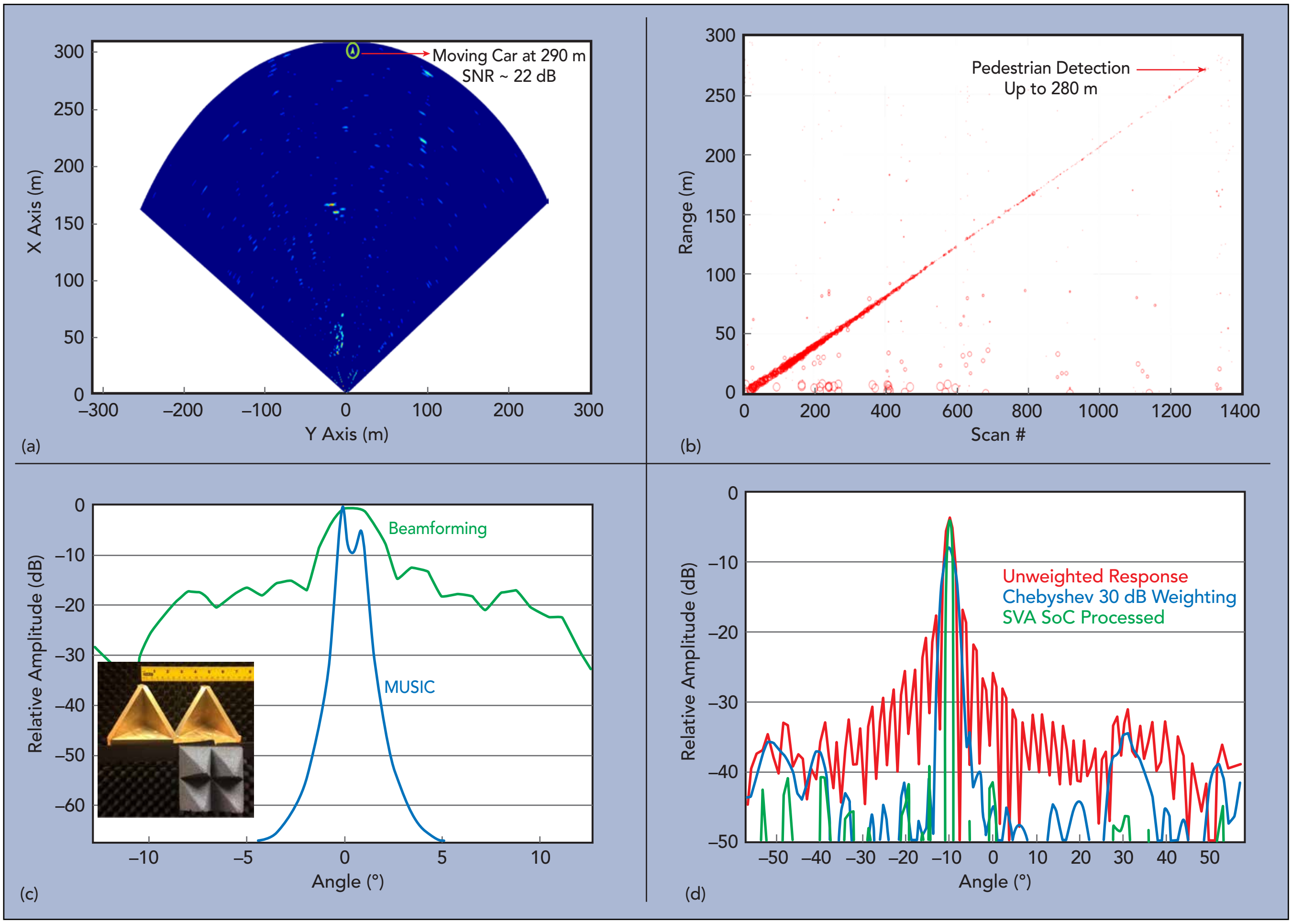
The D-ICU estimates the complex sum of the wideband self-interferer presented at each receiver input and removes the residual interferer before the correlators. The radar data control unit processes up to 1024 range bins for a single radar scan. The Winograd FFT engine manages up to 800 million points per second Doppler throughput. The beamforming engine throughput is 1.6 billion beams per second and implements a covariance matrix singular value decomposition engine, which supports direction-of-arrival algorithms such as MUltiple SIgnal Classification (MUSIC), estimation of signal parameters via rotational invariance techniques (ESPRIT) and Capon's algorithm, to further improve the angular resolution.

Compared to FMCW radars—or the newer variant fast chirp modulation (FCM)—the Uhnder architecture shifts the modulation complexity and precision to the high speed data converters and the DSP, where performance scales with the CMOS process node.

CMOS IMPLEMENTATION

The RoC was implemented in 28 nm high performance computing (HPC) CMOS technology and packaged in a fan-out wafer-level package (see ***Figure 8***). Digital signal and other radar computational processing is supported on chip with two floating point CPUs and two DSP engines. The overall software-defined hardware pipeline is capable of over 20 TOPS baseband processing.

At the package output reference plane, with 12 Tx active, the combined output power is approximately +19.6 dBm at 80 GHz and 125°C. The Rx noise figure measured at the analog-to-digital converter output is approximately 16 dB at 80 GHz and 125°C. Using an external PLL, the 77.5 GHz Tx phase noise at 1 MHz off-



▲ Fig. 9 Radar measurements: 25 mph moving car MIMO detection at 290 m with 22 dB SNR (a), beamforming pedestrian detection to 280 m (b), −108 dBsm corner reflectors in anechoic chamber after beamforming (green) and MUSIC (blue) (c) and angle sidelobe performance after digital beamforming (red), using a Chebyshev window (blue), applying SVA in hardware (d).

set is −110 dBc/Hz. Power consumption varies with the application; typically, the RoC consumes 15 W and is biased with 0.9, 1.3 and 1.8 V supplies.

Figure 9 shows the capability of the RoC. Using the MIMO mode, Figure 9a shows a car on boresight moving at 25 mph, instantaneously detected at 290 m with 22 dB SNR. In Figure 9b, the radar, operating in phased array mode, tracks a person on boresight moving out to 280 m. Figure 9c shows the difference in angular resolution with beamforming (green line) and MUSIC processing (blue line). The targets were two −10 dBsm corner reflectors in an anechoic chamber, spaced within about ±1 degree. Figure 9d shows the improvement in the unweighted digital beamforming sidelobe performance using windowing and spatially variant apodization implemented in the hardware.

SUMMARY

The Uhnder RoC is a software-defined radar, impervious to light and weather conditions and tremendously software configurable, enabling the user to choose the optimal spreading code depending on the objective of the radar system and the desired performance. By using a large number of virtual receivers, the RoC achieves best-in-class angular resolution. The results presented in this article represent just one implementation.

This RoC is the most integrated CMOS radar sensing platform to be reported.[2] It represents a significant advancement in automotive radar technology and offers a path for evolution. Combining standard CMOS semiconductor technology with advanced DSP concepts from the commercial communications industry, Uhnder has introduced a new capability for automotive sensors, based on an architecture that is software-defined and customizable, to address the most demanding sensor requirements. The approach is cost-effective, scalable and open to future innovation.■

References

1. Massachusetts Institute of Technology, "Working Together as a 'Virtual Telescope,' Observatories Around the World Produce First Direct Images of a Black Hole," *ScienceDaily*, April 10, 2019, www.sciencedaily.com/releases/2019/04/190410091028.htm.
2. V. Giannini et al., "A 192-Virtual-Receiver 77/79GHz GMSK Code-Domain MIMO Radar System-on-Chip," *IEEE International Solid-State Circuits Conference 2019*, www.uhnder.com/images/data/UHNDER_-_ISSCC_Paper.pdf.

Signal and Spectrum Analysis

Rohde & Schwarz RTO2064/B4

Rohde & Schwarz RTO oscilloscopes perform precise measurements at a high input sensitivity and very low inherent noise. The unique high-definition mode enables up to 16-bit resolution. With an acquisition rate of up to one million waveforms per second, these oscilloscopes detect sporadic signal faults very quickly.

The RTO Oscilloscopes are used with the FSW Series Signal Analyzers to provide a digitization path with up to 5 GHz of bandwidth.

The entire signal path from the spectrum analyzer's RF input to the oscilloscope's A/D converter is characterized with respect to amplitude and phase response. The digital data from the oscilloscope is mixed to the digital baseband and the measurement applications receive equalized I/Q samples. The connection between the oscilloscope and the analyzer is completely transparent to the user. The signal analyzer fully controls the oscilloscope, transferring, processing and equalizing the digital data.

Learn More

Key RTO Facts

- Precise measurements due to very low noise level: 1 % of full scale at 1 mV/Div and 1 GHz.
- High dynamic range due to single-core A/D converter.
- Wide selection of measurement functions: over 90 automated measurements.
- High-resolution touchscreen for ease of use.
- Color coding for clear overview.
- Class-leading 400 MHz logic analysis: 5 Gsample/s and 200 Msample memory on 16 channels.
- High definition: see more with up to 16-bit vertical resolution.

ROHDE&SCHWARZ
Make ideas real

Optimize beamforming
From bits to RF beams

Improve components for advanced antenna systems (AAS):

- Digital circuitry
- RF beamforming frontend
- Phased array antennas

ROHDE&SCHWARZ

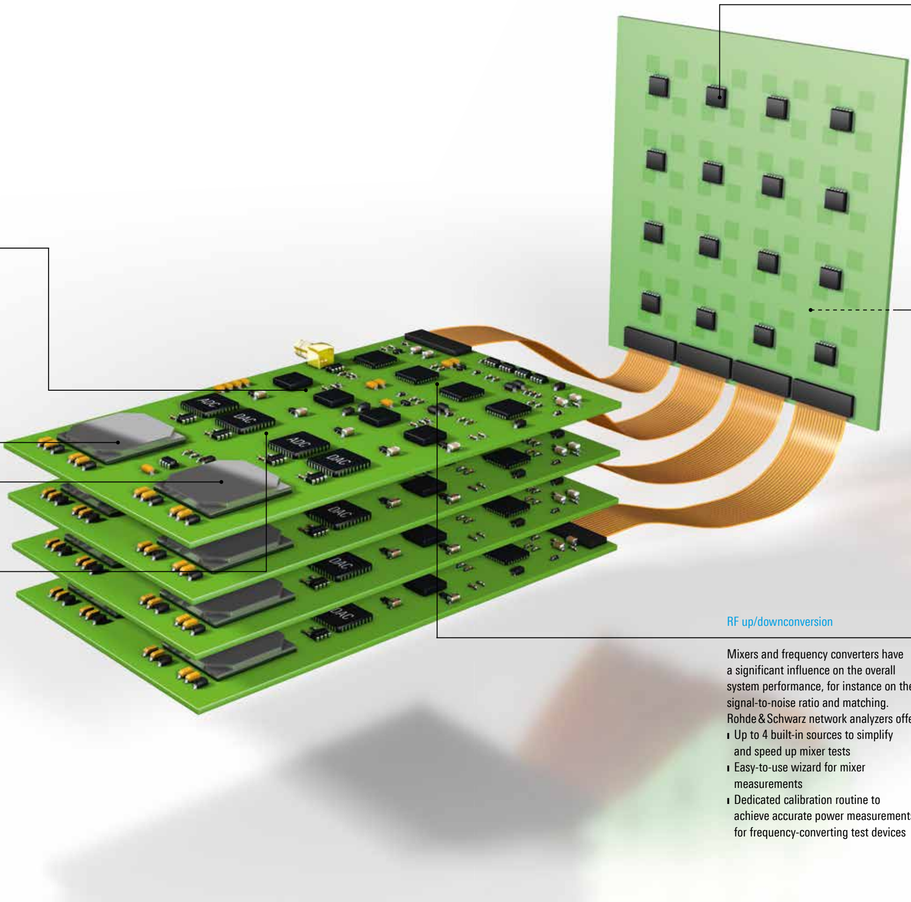
Your challenge

Radar, satellite communications and 5G NR use AAS with phased array antennas for beamforming. Hybrid beamforming combines the flexibility of digital beamforming with the efficiency of analog beamforming.

Increasing integration enables compact and cost-efficient AAS. To achieve accurate, reliable and efficient beamforming, it is necessary to understand and compensate for the nonlinear behavior of RF components.

While discrete components such as phase shifters, switches and amplifiers are tested conducted, highly integrated frontends with antenna-in-package (AiP) and system level tests require over-the-air (OTA) testing.

Rohde & Schwarz gives you the benefit of a well-coordinated portfolio of conducted and OTA test solutions.
More information at
www.rohde-schwarz.com/antennas



Analog beamforming / RF conditioning

Analog beamforming uses discrete phase shifters, gain control components or highly integrated beamforming ICs. The resolution in the phase shifter and the stability of the RF system define the beamforming capabilities.
Rohde & Schwarz multiport network analyzers offer:
- Parallel measurements on up to 24 ports and 40GHz to increase test speed and uncover any correlation between the various antenna links
- Two sources to support intermodulation measurements to characterize nonlinear components with just one test instrument
- Fast parallel testing in production on multiple DUTs
- For more information on RF amplifier testing, see: www.rohde-schwarz.com/power-amplifier

Filtering

Filters need to be sharp edged with a large attenuation to clean up the signal effectively.
Rohde & Schwarz network analyzers offer:
- Fast sweep times for quasi-realtime filter measurements
- Large dynamic range to see the full stop-band suppression

Digital section

Power and signal integrity, clock tree and SerDes PLLs: www.rohde-schwarz.com/signal-power-integrity

Transceivers

Data converter design: www.rohde-schwarz.com/data-converter
Beamforming needs aligned signals to feed the antennas. Accurate timing between the channels is essential; clock timing and signal flow need to be in sync.
Rohde & Schwarz oscilloscopes offer:
- Advanced trigger capabilities at full oscilloscope sampling speed to enable accurate timing measurements
- Statistics that provide insight into distribution of variance
- 4 phase coherent receivers to provide relative phase and amplitude differences between antenna signals

RF up/downconversion

Mixers and frequency converters have a significant influence on the overall system performance, for instance on the signal-to-noise ratio and matching.
Rohde & Schwarz network analyzers offer:
- Up to 4 built-in sources to simplify and speed up mixer tests
- Easy-to-use wizard for mixer measurements
- Dedicated calibration routine to achieve accurate power measurements for frequency-converting test devices

Antenna

Phased array antennas consist of many antenna elements to create the pointed RF beam. Rohde & Schwarz offers:
- Fast 3D antenna measurement solutions for near-field and far-field applications, including test software and various test chamber sizes with positioners to adapt to the test frequency and device size
- OTA power measurement setup for accurate power calibration at the system level
- Complementing OTA and modulated test solutions to support calibrated performance measurements such as EVM and ACLR

From bits to RF signals

Digital beamforming with appropriate phase and level weighting takes place in the baseband to generate individual streams. Many beams can be overlayed to enable multiple links via one RF system.

Complex digital chips such as FPGAs and ASICs have strict timings between the different sections of their booting sequences. To ensure the time sequence is in proper order, the R&S®RT-ZVC offers up to 8 channels to monitor the power consumption of the different sections over time. Other oscilloscope channels can simultaneously show e.g. SPI control commands.

Digital beamforming requires separate paths per stream with individual data converters. Time alignment between the different channels is essential since jitter and time variances between channels degrade beamforming accuracy.

Digital-to-RF simplifies the design with highly integrated SoCs and transceivers. The R&S®RTP oscilloscope offers:
- Time resolution down to 25 ps; statistic functions such as the histogram provide deep insight into variation and jitter trends
- 4 phase-coherent receivers for beamforming testing on RF signals to ensure proper phase and level per antenna signal
- Signal evaluation using R&S®VSE software
- Triggering on digital serial buses to evaluate timing between control signal and RF output

Beamforming leads to high signal path density on PCBs. This density and the high signal data rates means special attention must be given to board layout to ensure proper signal integrity (SI). Reflections and crosstalk are the main challenges when designing PCB signal paths, including vias and connectors. Together with our partner PacketMicro, we offer rugged probes for direct measurements on the PCB.

Vector network analyzers such as the R&S®ZNB offer advanced signal integrity (SI) features:
- Advanced time domain and eye diagram analysis
- Fast embedding/deembedding for impedance matching

The R&S®ZNA vector network analyzer makes mixer measurements easier than ever thanks to the following features:
- The R&S®ZNA four-port model offers up to four internal sources. Swept LO measurements and intermodulation measurements versus frequency on mixers are performed up to ten times faster compared with setups that use external generators.
- The R&S®ZNA determines the return loss and scalar conversion loss of mixers and converters with high precision using R&S®SMARTerCal.
- The analyzer performs relative phase measurements on frequency converters using vector error correction, a feature that is essential for digital beamforming, where the RF phase is controlled from the digital baseband through the complete RF chain.
- The R&S®ZNA offers a unique approach for phase and group delay measurements on converters without LO access.

The combination of R&S®RTP oscilloscope and R&S®ZVC multi-channel power probe enables synchronized measurement of analog, digital and RF signals.

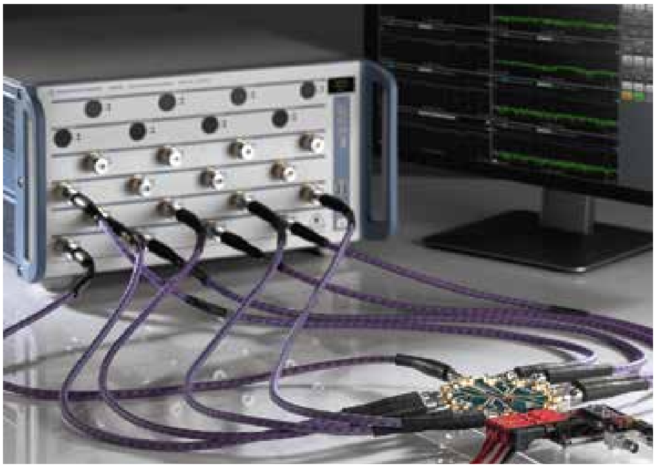
The R&S®ZNA vector network analyzer simplifies phase measurements on frequency-converting components such as mixers since no reference mixer is required.

Improve RF frontend

In a hybrid beamforming architecture, analog beam-forming is added to address a higher number of antenna elements. This narrows the beamwidth in a cost-efficient way and enables the RF signal to achieve a longer range. Modern highly integrated ICs offer digitally controlled beamforming. They help overcome the space limitations at higher frequencies where the antenna elements become rather small.

Important characteristics include:
- Phase and level control, resolution accuracy and stability per transmit and receive path
- Supported bandwidth in the forward and reverse link
- Maximum power level capability and linearity of the input and output – P1dB or P3dB – for the low noise amplifier (LNA) in the RX path and the output amplifier in the TX section.

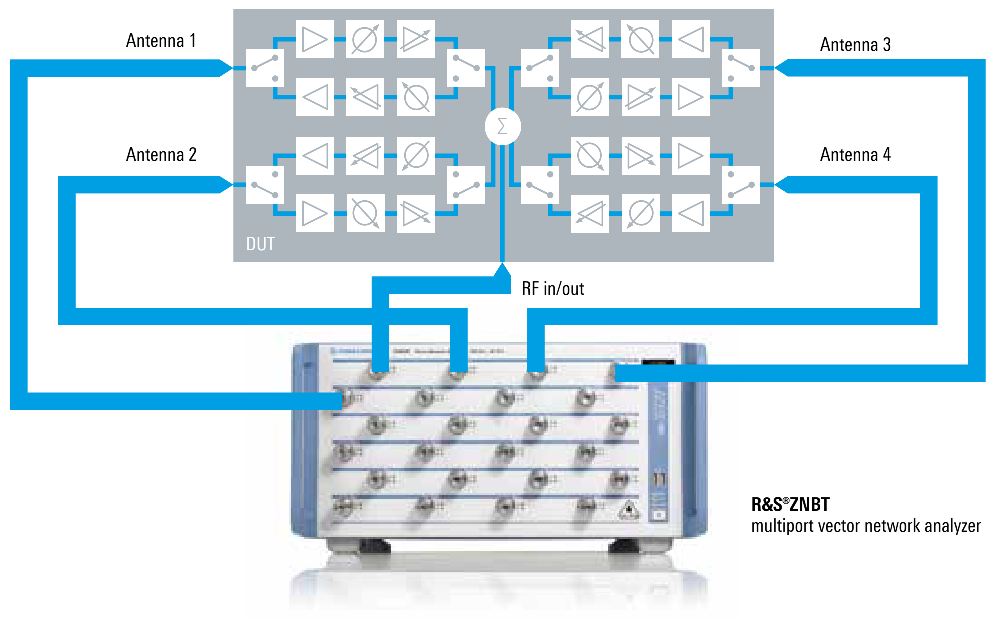
Vector network analyzers (VNA) support all measurements on one platform. The fastest way to characterize beamforming ICs is to connect to all ports on the device and run the measurements in one sequence without recabling. A true multiport VNA like the R&S®ZNBT offers many advantages:



Comprehensive beamforming testing with the R&S®ZNBT

- Parallel measurements on all ports of the DUT offer fastest test results and provide insight into cross-correlation between ports
- Up to 24 ports on a scalable platform enable direct connection to all DUT ports of single-ended or differential devices
- Large dynamic range to see the full DUT performance
- Two sources inside the R&S®ZNBT support intermodulation testing on nonlinear components
- First-to-market, true multiport VNA up to 40 GHz supports all major radar, satellite communications and 5G mmWave bands

Testing the beamformer IC using the multiport vector network analyzer R&S®ZNBT



Designers have a large degree of freedom in the structure of the beamforming network. Design decisions are made based on design goals such as the number of simultaneous beams (links), targeted beam width and range. Separate power amplifiers boost the output signal for radar or compensate for losses from power splitters integrated into the signal chain.

All amplification stages need to support the wideband signals used in radar, satellite communications or 5G NR. This can easily be verified with the powerful wideband signal generation and analysis solution offered with the R&S®SMW200A and the R&S®FSW. They offer:
- Wide frequency range coverage up to 43 GHz for all important 5G applications
- Wide internal signal bandwidth of 2 GHz that simplifies test setup
- Built-in signal creation and analysis for all signal types from radar to 5G NR

Antenna and system level

Integration is an important enabler for compact, cost-efficient beamforming systems. Antenna-in-package (AiP) is a logical next step in integration. It is not possible to verify antenna modules or AiP devices such as fully integrated 5G mmWave RFICs with a conducted test. A controlled OTA (over the air) link is the only way to get reliable performance information.

Rohde & Schwarz benefits from a long history in antenna measurements with near-field (NF) and far-field (FF) solutions. The R&S®AMS32 antenna measurement software supports fast and easy characterization of single antenna elements or complete phased arrays using amplitude and phase information measured by a vector network analyzer. The integrated algorithms for NF-FF transformation make it possible to perform antenna characterization of arrays that exceed the maximum size for FF conditions in a smaller chamber.

The R&S®SMW200A vector signal generator together with the R&S®FSW signal and spectrum analyzer form a powerful test setup for RF amplifiers.

R&S®ATS1000: one compact OTA chamber for antenna and RF performance measurements

Based on the size and frequency range of the DUT, chambers with different form factors are required. Large walk-in chambers to small benchtop solutions are available to meet different requirements. 5G NR includes mmWave frequencies to support the maximum data rates enabled by high integration in infrastructures and handset frontends.

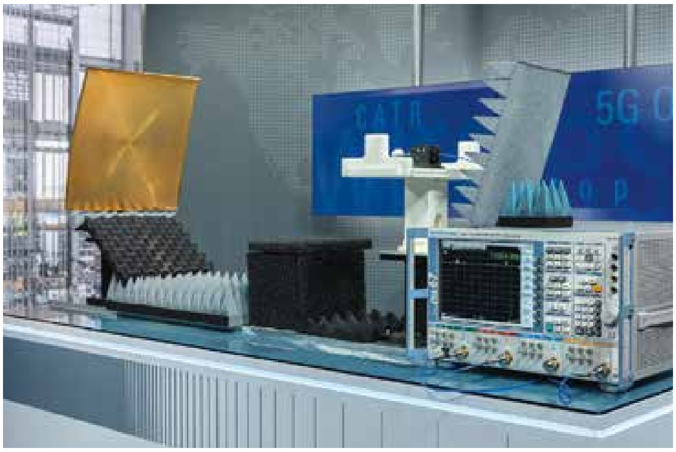
The R&S®ATS1000 antenna test system family is mmWave optimized for 5G applications. It offers:

- Far-field conditions in a compact and mobile form factor for flexible use in lab environments without the need for a fixed installation
- Multiuse for antenna characterization and modulation performance tests like EVM and ACLR when used together with appropriate RF instruments
- Precision positioner for accurate 3D antenna patterns allow exact evaluation of beamforming capabilities
- Device characterization under extreme temperature ranges using an integrated quasi-transparent temperature bubble, an especially important feature for highly integrated devices with active RF functions and AiP
- Integrated compact antenna test range (CATR) to increase the maximum test size for far-field conditions

For generic lab setups, the CATR system is available as an open benchtop solution. This is more cost-efficient and provides easy access to the test object between measurements. It is ideal for tuning the design while maintaining a large quiet zone with a homogeneous far field. Calibrating the output power of a device requires the highest accuracy offered by power meters, no matter if conducted or OTA. The R&S®NRPM OTA power measurement solution is a unique integration of antenna and power meter, offering easy power measurements at any position.

Functional beamforming tests are as simple as measuring signal strength at different positions. Using multiple antenna modules, the R&S®NRPM provides direct information on the direction of the beam and the signal strength of the main lobe and side lobes in a fast and cost-efficient way.

Cost-efficient OTA solution: R&S®ATS800B benchtop version with feeder antenna, reflector and positioner to create uniform planar waves paired with an R&S®ZVA vector network analyzer for antenna characterization



OTA power calibration and functional beamforming tests made easy with the R&S®NRPM OTA power measurement solution

Service that adds value

- Worldwide
- Local und personalized
- Customized and flexibel
- Uncompromising quality
- Long-term dependability

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, monitoring and network testing. Founded more than 80 years ago, the independent company which is headquartered in Munich, Germany, has an extensive sales and service network with locations in more than 70 countries.

www.rohde-schwarz.com

Sustainable product design

- Environmental compatibility and eco-footprint
- Energy efficiency and low emissions
- Longevity and optimized total cost of ownership

Certified Quality Management
ISO 9001

Certified Environmental Management
ISO 14001

Rohde & Schwarz training

www.training.rohde-schwarz.com

Regional contact

- Europe, Africa, Middle East | +49 89 4129 12345
  customersupport@rohde-schwarz.com
- North America | 1 888 TEST RSA (1 888 837 87 72)
  customer.support@rsa.rohde-schwarz.com
- Latin America | +1 410 910 79 88
  customersupport.la@rohde-schwarz.com
- Asia Pacific | +65 65 13 04 88
  customersupport.asia@rohde-schwarz.com
- China | +86 800 810 82 28 | +86 400 650 58 96
  customersupport.china@rohde-schwarz.com

R&S® is a registered trademark of Rohde & Schwarz GmbH & Co. KG
Trade names are trademarks of the owners
PD 3607.9720.32 | Version 01.00 | May 2019

Data without tolerance limits is not binding | Subject to change

© May 2019 | Rohde & Schwarz GmbH & Co. KG | 81671 Munich, Germany

3607972032

3607.9720.32 00.01 PDP 1 en

Easy Measurement of Radar Pulse Stability

Rohde & Schwarz
Munich, Germany

Radars not only receive echoes from the targets they detect, they receive echoes from surrounding objects such as trees, buildings and ocean waves. These incidental echoes, known as clutter, are of no interest and can impair radar performance. Signal processing in advanced radar systems detects and suppresses these unwanted reflections, by comparing the phases and amplitudes of successive echoes and displaying only moving targets, for example. The greater the phase and amplitude stability of the transmitted pulses, the better the results from signal processing. With high quality radar signals, any phase and amplitude variation can be assumed to be from the target, not from any instabilities in the transmitter. Thus, knowing the phase and amplitude stability of the transmitted pulses is crucial to assessing the sensitivity of a radar system to detect targets with a very small radar cross section, such as micro aerial vehicles. Power amplifiers (PA), in particular, can degrade stability, making precise measurement of the PA necessary to determine overall system sensitivity.

COMPLEX MEASUREMENT, SIMPLE SETUP

Historically, high sensitivity measurements of the phase and amplitude stability of pulses required a complicated test setup with multiple instruments. A new option for the Rohde & Schwarz FSWP phase noise analyzer and VCO tester makes these measurements easy and straightforward. The R&S FSWP-K6P option is an enhancement to the R&S FSWP-K6 pulse measurement option, specifically intended to characterize pulse stability. The R&S FSWP-K6P option uses the FSWP hardware, which was designed with very low phase noise, capable of measuring phase and amplitude stability with higher sensitivity than a spectrum analyzer.

▲ **Fig. 1 The R&S FSWP phase noise analyzer feeds a pulsed signal to an amplifier, then analyzes the amplifier's output.**

The R&S FSWP can generate pulses like a radar system, which feed the amplifier or other device being tested. The amplifier output is connected back to the R&S FSWP, which analyzes the signal. For this complex and highly sensitive measurement, the test setup could not be any simpler, as seen in ***Figure 1***.

THEORY

Since the phase noise of the local oscillator in the R&S FSWP and the generated pulses are identical or correlated, the phase noise can be suppressed, leaving only the phase change caused by the device being tested.

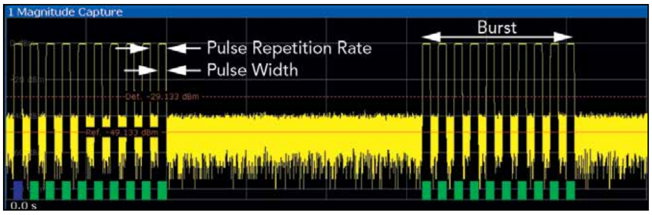


Fig. 2 The burst signal consists of 10 pulses followed by a pause.

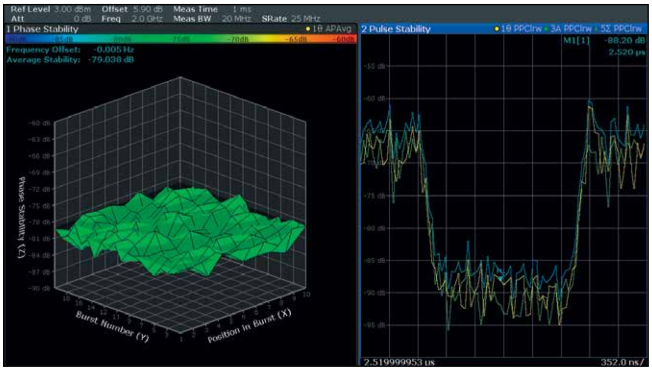


Fig. 3 Phase deviation from the average of each pulse for all recorded bursts (left). Pulse-to-pulse phase stability (yellow), amplitude stability (green) and sum of the two (blue) averaged over all pulses (right).

This residual measurement has a sensitivity of less than −80 dB for pulse-to-pulse phase and amplitude stability. If the source in the R&S FSWP is not adequate for the application, the R&S FSWP offers users the flexibility to insert an external source as a local oscillator for the measurement.

The dB values for phase stability are calculated from the equation:

$$\text{Phase Stability} = 10\log\left[\frac{1}{N-1}\sum_{i=1}^{N-1}(\theta_{i+1}-\theta_i)^2\right]$$

where θ_i is the phase at the sampling point of the ith of N pulses. An average pulse-to-pulse phase deviation on the order of 0.1 mrad corresponds to –80 dB. A similar calculation applies to amplitude stability.

Typical radar applications do not use simple pulses; they employ bursts or complex pulse sequences (see ***Figure 2***). Consequently, burst signals are required to accurately test radar components, since components will heat up during the "on" portion of the burst signal, and this has a strong effect on the phase and amplitude stability. The R&S FSWP can generate pulse sequences and bursts, so the results reflect the performance of the device being tested under actual radar operation.

OUTPUT PRESENTATION

With the R&S FSWP-K6P option, users choose whether to make measurements using the broadband spectrum analyzer or the more sensitive phase noise tester. With the latter, users can either measure the pulsed signal directly or employ the residual test mode using internally generated pulses to stimulate the device being tested.

Phase and amplitude stability can be displayed for each individual pulse, with the deviation from the average at each sampling point in a pulse calculated and displayed. The R&S FSWP can average the values over an entire burst or calculate the difference between pulses, delivering pulse-to-pulse phase and amplitude stability. Both of these averaging techniques produce smoother, more instructive traces (see ***Figure 3***).

The better the amplitude and phase stability within a radar pulse, the more information a radar system can extract from the received signal. Making stability measurements with the required level of sensitivity used to be complex and costly. With the new option for the R&S FSWP phase noise analyzer and VCO tester, these measurements become easy and straightforward.■

Signal and Spectrum Analysis

Rohde & Schwarz FSW50/B5000

The R&S FSW signal and spectrum analyzer provides low phase noise, wide analysis bandwidth and straightforward and intuitive operation.

Learn More

Key FSW Facts

- Frequency range from 2 Hz to 8/13.6/26.5/43.5/50/67/85 GHz (with external harmonic mixers from Rohde & Schwarz up to 110 GHz)
- Low phase noise of –137 dBc (1 Hz) at 10 kHz offset (1 GHz carrier)
- –88 dBc dynamic range (with noise cancellation) for WCDMA ACLR measurements
- Up to 2 GHz analysis bandwidth
- < 0.4 dB total measurement uncertainty up to 8 GHz
- Real-time analysis up to 512 MHz bandwidth
- High-resolution 12.1" (31 cm) touchscreen for convenient operation
- Multiple measurement applications can be run and displayed in parallel

ROHDE&SCHWARZ
Make ideas real

Integrated 140 GHz FMCW Radar for Vital Sign Monitoring and Gesture Recognition

K. Vaesen, A. Visweswaran, S. Sinha, A. Bourdoux, B. van Liempd and Piet Wambacq
imec, Leuven, Belgium

An integrated, high performance, 140 GHz frequency-modulated continuous wave (FMCW) radar system enables the detection of minute motion, offering utility for various applications. Its main features are described in this article, including transceiver characterization and measurements of vital signs using a 2×2 MIMO radar assembly.

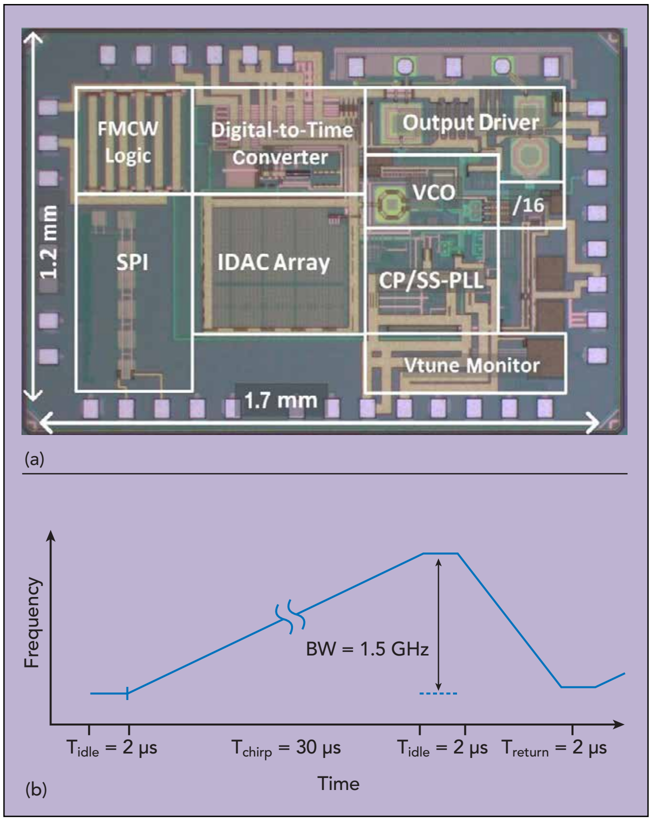
Since the introduction of the first radar systems in the early 1930s, radar technology has evolved significantly. During this time, researchers have reduced the size, power consumption and cost dramatically, while increasing resolution and enhancing the algorithmic computational capabilities. Development and advances in IC technology have enabled a class of low-power and short-range mmWave radars with carrier frequencies in the 30 to 300 GHz range (10 to 1 mm wavelength), adding to the mass of wireless applications pervading society. Today, radars are embedded in a number of cars, as parking aids or for safety, detecting pedestrians, other road users and objects at a few meters.

These high frequency radars with small form factors can be integrated almost invisibly in numerous devices, to enable a broad range of smart and intuitive applications, such as building security (e.g., people counting and intruder detection), remote health monitoring of automobile drivers, monitoring the vital signs of patients and gesture recognition for intuitive man-machine interaction. The number of use cases will imminently grow as radar systems offer finer range resolution, smaller footprint, higher energy efficiency and lower cost.

A MULTITUDE OF FLAVORS

Although all radar systems follow the same basic principle, their various implementations determine the cost, size, power consumption and capability. Radars can differ by the frequency of the carrier (e.g., 2.4, 8, 60, 79, 140 GHz), bandwidth, type of carrier modulation (e.g., frequency or phase) and pulsed or continuous wave (CW). By necessity, small radars with high resolution operate at high carrier frequencies with wide bandwidth. As resolution is inversely proportional to bandwidth, radar systems operating above 100 GHz can offer very broadband operation, which enables fine range resolution. A Doppler shift is observed as a change in frequency of the wave reflected from a target, when the source and target are moving closer together or further apart. This shift can be measured more precisely at higher frequencies to provide a more exact determination of a target's velocity.

In time, data from multiple sensors—which may add LiDAR, hyperspectral imagers, infrared cameras and ultrasonic sensors to radar—will be merged on a common platform, each offering advantages and having limitations. Radar technology is an environmentally robust solution and can serve as an alternative to optical im-



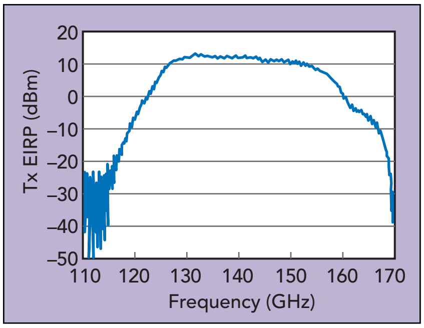
▲ **Fig. 1 16 GHz FMCW PLL IC (a) and chirp modulation response (b).**

age sensors when privacy concerns or regulations prohibit using cameras. Supplementing the development of radar sensor technology, advances in physical pattern recognition are driving advanced machine learning techniques to classify objects or gestures using radar Doppler signatures.

140 GHz FMCW RADAR TRANSCEIVER IC

Targeting vital sign detection and gesture recognition, imec has developed a 140 GHz FMCW radar transceiver with on-chip antennas. The radar operates over a range from 0.15 to 10 m and has 11 mm range resolution, achieved with 13 GHz of RF bandwidth centered at 145 GHz. The transceiver IC is fabricated with a production 28 nm bulk CMOS technology, which enables a low-cost solution.

The main building block of the radar is an integrated transceiver featuring on-chip antennas and a sub-sampling digital phase-locked loop (PLL), which forms the FMCW chirp generator. Antennas integrated on the same chip couple with each other, resulting in leakage between the transmit (Tx) and receive (Rx) paths; however, the radar features on-chip leakage cancellation in the receiver to circumvent this effect, which can result in gain compression and DC offsets. The radar receiver measures the difference between the frequency of the reflected and transmitted RF chirps. This frequency difference is translated into the MHz range, making amplification, filtering and analog-to-digital conversion much easier than with other radar waveforms (e.g., phase-modulated CW).



▲ **Fig. 2 Transmitter EIRP.**

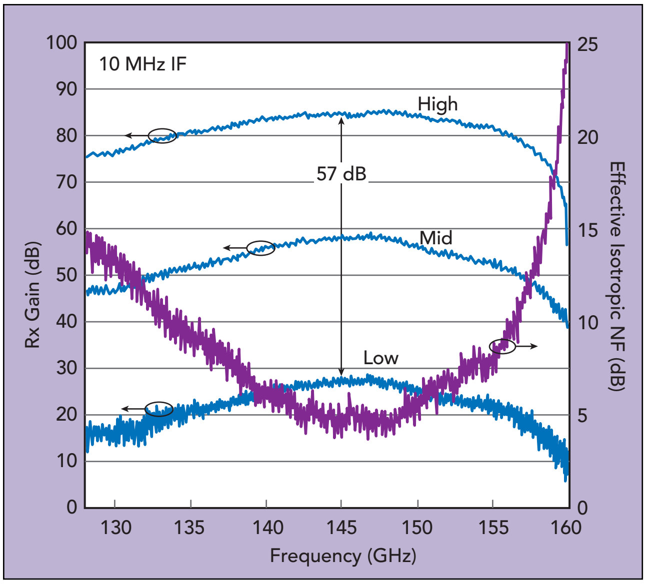
The PLL generates a frequency modulated CW signal, where the carrier frequency is modulated over a wide bandwidth using a linear sawtooth waveform. The repetition rate of the modulating sawtooth is known as the chirp rate. Imec has developed and characterized a 16 GHz, fast chirping PLL fabricated with a 28 nm bulk CMOS process (see ***Figure 1a***). This PLL can operate both in a classical mode as well as a divider-less sub-sampling mode, offering flexibility and high performance. The PLL achieves a wide chirp bandwidth of 1.5 GHz in only a 30 µs chirp period, allowing fast sawtooth frequency modulation (see ***Figure 1b***).

Multiple transceiver ICs were used to create a 2×2 MIMO radar, augmenting the range and speed detection capabilities of a single-input-single-output radar. MIMO increases the azimuth angular resolution, providing additional information to resolve target orientation.

In the MIMO configuration, a central 16 GHz chirp signal is distributed to multiple Tx inputs. The signal is upconverted to 144 GHz using a cascade of two frequency triplers, after which it is amplified and transmitted via the on-chip antennas. The radiated chirp is reflected by targets broadside to the antennas and captured by the on-chip receiver. The reflected signal is amplified in the receiver and compared with a replica of the initial chirp signal, using a mixer. The delay of the received signal, corresponding to the time-of-flight to the target and back, results in an instantaneous frequency offset compared to the reference chirp. The greater the distance to the target, the greater the relative frequency shift and the range of the target is obtained from the frequency of the down-converted signal. The analog output from the receiver is converted to a digital signal, enabling signal processing to extract the range and speed.

The transmitter is characterized by its effective isotropic radiated power (EIRP). For the integrated 140 GHz prototype, the measured EIRP is as high as 11 dBm and has a 3 dB bandwidth from 127 to 154 GHz (see ***Figure 2***). This is the highest recorded EIRP in D-Band for a single integrated transceiver compared to currently published state-of-the-art ICs (see ***Table 1***). The receiver's performance is characterized by its noise figure and conversion gain: 8 and 84 dB, respectively (see ***Figure 3***). The total power consumption of the radar transceiver IC is less than 500 mW.

Radars with frequencies below 100 GHz require large off-chip antennas, which are usually fabricated on high frequency laminates and attached to the IC via flip-chip or wire bond interfaces. Developing and implementing these complex antenna-on-package modules significantly contributes to the cost and size of the final radar system. However, the higher the frequency of the carrier—the smaller its wavelength—



▲ **Fig. 3 Receiver gain and effective isotropic noise figure.**

the more the size of the antenna element is reduced. For carrier frequencies above 100 GHz, the antenna is sufficiently small that it can be integrated on the radar chip. This antenna-on-chip solution offers clear size and cost advantages compared to off-chip antennas on printed circuit boards (PCB). When integrated on-chip, there is no need for mmWave transitions between the IC and PCB that ultimately degrade bandwidth and signal strength. In this design, the antenna elements were integrated into the passivation layer of the transceiver, with the Tx and Rx antennas 2 mm apart to minimize crosstalk (see ***Figure 4***).

For many applications, including gesture recognition, high angular resolution is needed to capture gestures in three dimensions. This can be accomplished with MIMO radar, as they transmit mutually orthogonal signals from multiple Tx antennas, which are then extracted from each of the Rx antennas. Imec has demonstrated a 1×4 virtual array with three transceiver ICs, including two transmitters and two receivers, resulting in a 2×2 MIMO assembly shown in ***Figure 5***. The configuration is called "1×4 virtual" because the angular resolution corresponds to the resolution obtained by the four elements in a row. In this configuration, the central chirp signal is distributed to the separate transceiver chips on a PCB. Using the super-resolution MUSIC algorithm, a fine angular resolution of 7.5 degrees is achieved with a complete MIMO radar form factor of only a few square centimeters.

VITAL SIGN DETECTION AND GESTURE RECOGNITION

Two main applications are envisioned for the 140 GHz MIMO radar: vital sign detection and gesture recognition.

The feasibility of detecting vital signs in real-time, including monitoring heart rate and breathing, have been demonstrated. The 1×4 MIMO radar captured the 1 and 5 Hz beats of a "reference heart"—a speaker diaphragm with 1 mm displacement—as shown in ***Figure 6a***. In a second experiment, the feasibility of measuring micro-skin motion in real-time, which reflects a person's respiration and heartbeat, was demonstrated (see ***Figure 6b***). In the future, greater processing capability will enable more accurate distinctions between heartbeat and respiration.

TABLE 1

SINGLE CHIP mmWAVE RADAR TRANSCEIVERS

Reference	***This Work***	***Wuppertal, Trans. THz 2016***[1]	***TI, JSSC 2014***[2]	***TI, ISSCC 2018***[3]	***IHP, IMS 2016***[4]	***I. Nasr, Google, IFX, JSSC 2016***
Technology	28 nm CMOS	0.13 µm SiGe	65 nm CMOS	45 nm CMOS	0.13 µm SiGe	0.35 µm SiGe
Radar Type	FMCW	FMCW	Pulsed	FMCW	FMCW	FMCW
Antenna	On Chip	On Chip	In Package	In Package	On Chip	In Package
Frequency (GHz)	145	240	160	79	122	60
RF Bandwidth (GHz)	13	60	7	4	5.8	7
Range Resolution (cm)	1.1	0.3	2.1	3.8	2.6	2.1
Channels	1Tx-1Rx	1Tx-1Rx	4Tx-4Rx	3Tx-4Rx	1Tx-1Rx	2Tx-4Rx
Single Path Tx Power/EIRP (dBm)	11.5 (EIRP)	5	4	10.8	5	4
Rx Gain (dB)	80	10	42.5	NA	NA	19
Noise Figure (dB)	8	21	22.5	18	NA	9.5
IF Bandwidth (MHz)	17	18	100	15	NA	1
Chip Size (mm^2)	6.5	3.2	20	22	10.35	20.2
Power Diss. for All Channels (mW)	500	1800	2200[+0]	3500[++]	NA	990[x]

[+]Includes On-Chip PLL and ADC
[++]Includes On-Chip PLL, ADC and DSP
[0]Power Dissipation in Pulsed Operation
[x] RF Front-End Only with On-Chip VCO

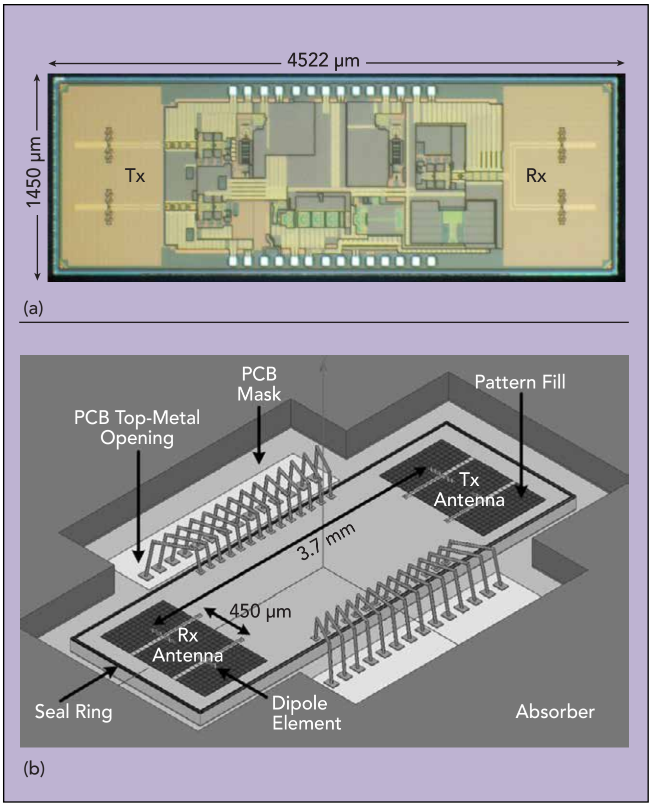


Fig. 4 **Transceiver IC (a) and packaging (b), showing the Rx and Tx antennas integrated on opposite sides of the IC.**

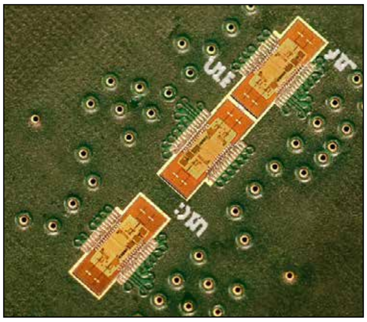


Fig. 5 **MIMO radar board with three transceiver ICs.**

A portable 1×4 MIMO radar demonstrator is currently being built to measure vital signs in real-time. To capture gestures and motion, the radar must have high angular resolution, which is achieved with larger MIMO arrays. A 4×4 virtual MIMO radar, realized by one row and one column of four transceiver ICs each, is currently being developed and will be complemented with additional processing capabilities for micro-Doppler information and machine learning techniques. Machine learning will train the system using classified data to recognize the Doppler signatures of moving objects.

SUMMARY

An extremely compact, fully integrated 140 GHz FMCW radar transceiver in 28 nm CMOS has been demonstrated. Centered at 145 GHz and up-converted from a 16 GHz PLL chirp signal, an RF bandwidth of 13 GHz yields 11 mm range resolution. The IC contains Tx and Rx signal paths and integrated antennas. For the transmitter, a record EIRP of 11 dBm from a single element was measured, while the receiver achieved a noise figure and conversion gain of 8 and 84 dB, respectively. In a 2×2 or 1×4 virtual MIMO configuration, fine angular resolution was achieved. These features enable the radar to detect vital signs and gestures. Imec is currently building portable demonstrators to further show the capability of its 140 GHz MIMO radar systems.

Imec is also developing other compact and low-cost radar sensing solutions for IoT applications, including 8, 60 and 79 GHz CMOS-based radars. The ICs are designed to achieve state-of-the-art performance while avoiding "specialty" semiconductor technologies.■

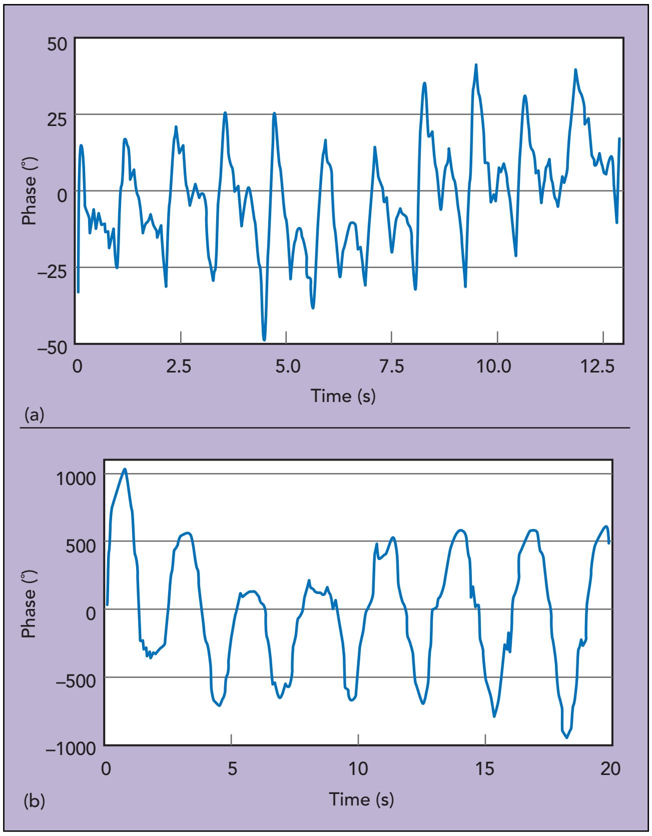


Fig. 6 **MIMO radar vital sign measurements: reference heartbeat (a) and skin motion reflecting heartbeat and respiration (b).**

ACKNOWLEDGMENT

The authors thank Panasonic and Sony for their support.

References

1. J. Grzyb et al., "A 210–270-GHz Circularly polarized FMCW Radar with a Singlelens-Coupled SiGe HBT Chip," *IEEE Trans. THz Sci. Technol.*, Vol. 6, 2016, pp. 771–783.
2. B. Ginsburg et al., "A 160 GHz Pulsed Radar in 65nm CMOS," *IEEE JSSC.*, Vol. 49, No. 4, April 2014, pp. 984–995.
3. B. Ginsburg et al., "A Multimode 76-to-81GHz Automotive Radar Transceiverwith Autonomous Monitoring," *ISSCC*, 2018, pp. 158–159.
4. H.J. Ng et al., "Miniaturized 122 GHz System-on-Chip Radar Sensor with On-Chip Antennas Utilizing a Novel Antenna Design Approach," *IEEE MTT-S Int. Microwave Symp.*, 2016.

Advanced methods for analyzing ultra wide automotive radar signals

White paper

The content of this white paper was previously presented at
EDI CON China 2018, Shanghai

ROHDE&SCHWARZ

Electro Rent

Laura Sanchez

White paper | Version 01.00

Table of contents

Automotive FMCW radars typically operate between 76 GHz and 77 GHz. In some countries, the frequency range between 77 GHz and 81 GHz has become available for automotive radar applications. The distance resolution of an FMCW radar is proportional to its signal bandwidth. Therefore, automotive radar manufacturers are already developing FMCW radars with bandwidths of several GHz to get the most out of the available frequency range.

In addition to signal frequency and bandwidth, the signal linearity and chirp duration determine radar performance. It is therefore important to analyze automotive radar signal parameters such as chirp length, chirp rate and frequency deviation.

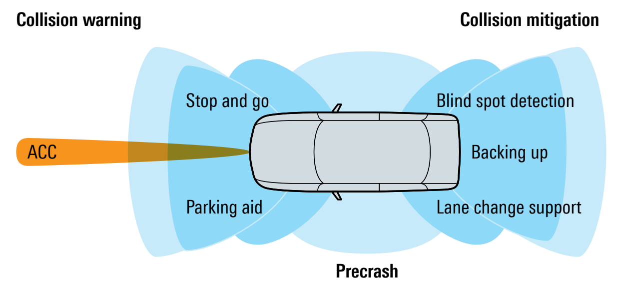
This paper will review different ways to overcome the challenges of RF measurements in the E band for ultra wide signals. It will look at the demodulation and analysis of a wideband automotive radar signal and discuss the results and main performance parameters.

Introduction

Radar makes it possible to quickly and precisely determine the velocity, distance and azimuth angle of multiple objects.

Automobiles advanced driver assistance systems (ADAS) are increasingly being equipped with radar sensors to support drivers in critical situations and help reduce the number of accidents.

Fig. 1: Vehicles are increasingly equipped with radar sensors



In addition to the 77 GHz band (76 GHz to 77 GHz), the 79 GHz band (77 GHz to 81 GHz) has become available in some countries for automotive radar. Therefore, the automotive industry is already developing radar sensors operating in the E band with signals several GHz wide.

The distance resolution of a radar sensor is proportional to its signal bandwidth, i.e. the wider the bandwidth, the better the radar sensor's ability to distinguish between different targets that are close to each other.

Signal bandwidth alone is not enough to ensure the distance resolution or radar performance. Other signal parameters such as frequency, power, frequency deviation from linear FM chirp, signal to interference ratio, chirp rate and chirp duration need to be thoroughly tested during development and verification of radar components.

Analyzing 5 GHz wide automotive signals in the E band represents a challenge for traditional test and measurement equipment. In this paper, we show how a high-performance signal and spectrum analyzer combined with an oscilloscope helps automotive radar manufacturers overcome this challenge.

RF measurements in the E band (60 GHz to 90 GHz): spectrum analyzer versus external harmonic mixers, aspects to consider

Spectrum analyzers are a common tool for evaluating RF parameters such as frequency, EIRP, occupied bandwidth and out-of-band emissions during development, production and verification of radar sensors. High-performance spectrum analyzers operating up to 90 GHz are available today to measure RF signals transmitted by radars operating between 76 GHz and 81 GHz directly. If a spectrum analyzer does not support such high frequencies, its frequency range can be extended using external harmonic mixers. This section points out the main aspects to consider when using these different approaches.

Measurements in the E band with external harmonic mixers

Most spectrum analyzers do not directly support frequencies as high as 79 GHz. In this case, the frequency range of the analyzer can be extended with external harmonic mixers. A harmonic of the LO signal produced in the mixer is used to convert the input signal to the spectrum analyzer IF frequency.

Fig. 2: The R&S®FSW26 (up to 26.5 GHz) can be used with the R&S®FS-Z90 external harmonic mixers (60 GHz to 90 GHz) to measure RF signals in the E band.

The frequency conversion done by the mixer can be expressed with the following equation:

$$\left| m \cdot f_{LO} \pm n \cdot f_{RF} \right| = f_{IF}$$

Where:

m is the order of the harmonic of the LO signal (m = 1, 2, 3 ...)
n is the order of the harmonic of the microwave input signal (n = 1, 2, 3...)
f_{LO} is the frequency of the local oscillator
f_{RF} is the frequency of the input signal
f_{IF} is the intermediate frequency

Looking at the formula above, one can deduce that in addition to the input signal at the wanted receive frequency, there are also a number of unwanted images and mixing products. External harmonic mixers do not have a preselection filter and do not provide image rejection. Therefore, unwanted mixing products will be present in the spectrum as shown in Fig. 3.

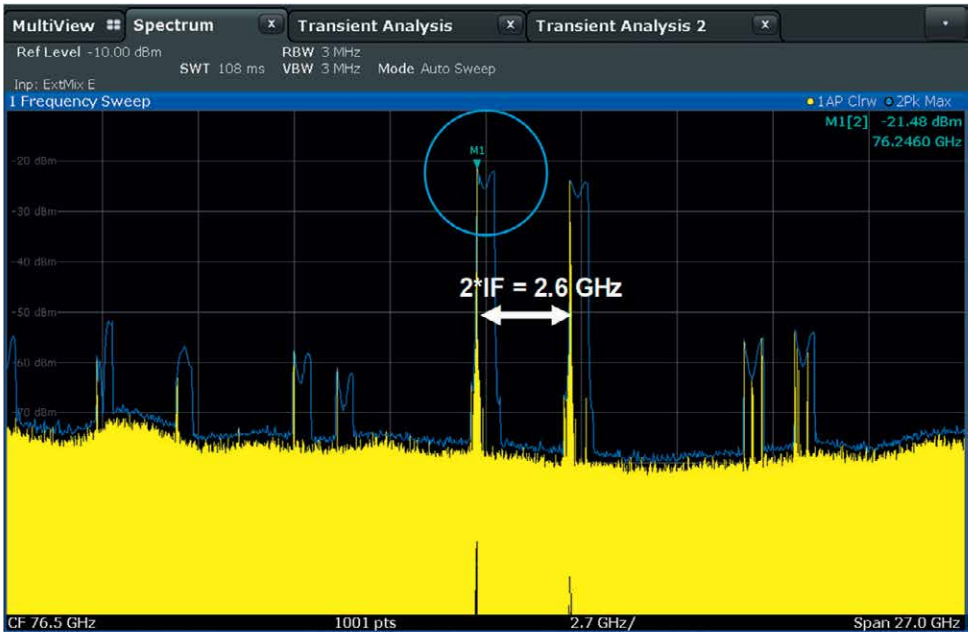


Fig. 3: Spectrum from 60 GHz to 90 GHz measured with the R&S®FS-Z90 external harmonic mixer connected to the R&S®FSW43. The wanted signal at 76 GHz is 500 MHz wide. The closest image is located at twice the spectrum analyzer intermediate frequency from the signal. Other unwanted mixing products and their images are also present.

The delta between the wanted signal and its image is twice the spectrum analyzer intermediate frequency ($2 \cdot f_{IF}$). If the signal bandwidth is wider than ($2 \cdot f_{IF}$), the wanted signal and its image will overlap in spectrum.

The R&S®FSW has an intermediate frequency (IF) of 1.3 GHz, so it provides an image-free frequency range of 2.6 GHz for spectrum analysis with external harmonic mixers.

To ensure unambiguous spectrum measurements, it is necessary to filter out unwanted image frequencies.

Software algorithms using double sweep techniques can identify and suppress unwanted mixing products. These algorithms work well with static signals, but reach their limitations when working with pulsed or transient signals, which are usual in radar applications.

Measurements in the E band with a signal and spectrum analyzer (2 Hz to 90 GHz)

The R&S®FSW85 high-performance signal and spectrum analyzer covers frequencies between 2 Hz and 85 GHz or optionally 90 GHz.

For frequencies between 8 GHz and 85 GHz, the analyzer features hardware preselection to reject unwanted image frequencies. The frontend is equipped with a narrow bandpass filter implemented with YIG technology. The center frequency of the YIG filter corresponds to the input signal, and its narrow band allows the unwanted image frequencies to be filtered out.

After the YIG filter, the mixer converts the input RF signal to an IF of 1.3 GHz. In Fig. 4 you can see an image-free, 500 MHz wide signal at 76 GHz.

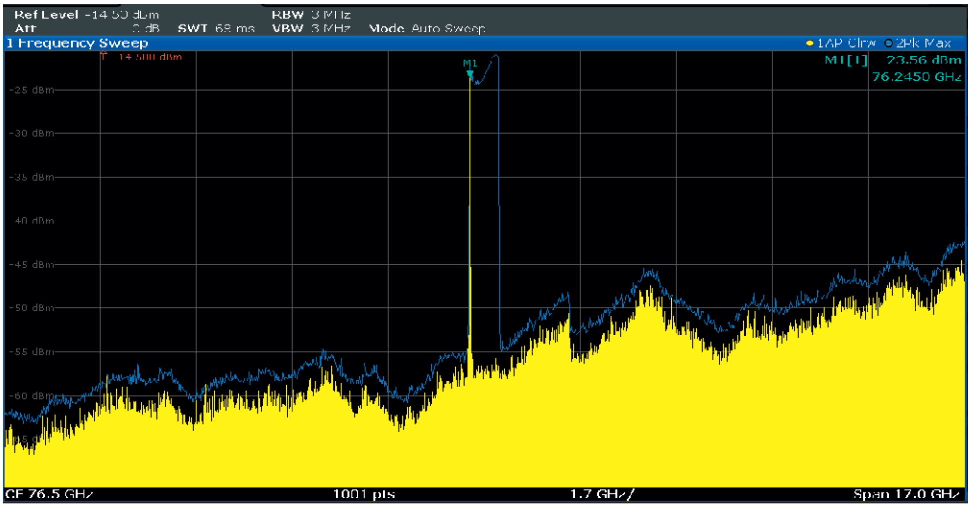


Fig: 4. Spectrum of a 500 MHz bandwidth FMCW radar signal at 76 GHz, measured with an R&S®FSW85

Analyzing the spectrum with a single instrument that supports the required frequency has several advantages over external harmonic mixers:
- Gapless spectrum from DC to 85/90 GHz
- Inherent image suppression with preselection/YIG filter in spectrum analyzer mode
- Better level adjustment: internal adjustment of attenuators, etc.
- Less cabling
- Higher dynamic range for SEM measurements

An optional external preamplifier up to 85 GHz improves the spectrum analyzer's noise floor. This is especially useful when measuring radar signals over the air.

Fig. 5: R&S®FSW85 signal and spectrum analyzer with the R&S®HA-Z24E external preamplifier (1 GHz to 85 GHz)

Ultra wideband measurements with spectrum analyzers

The demand for analysis bandwidth is continuously increasing, driven by industry demands for aerospace and defense, wireless and automotive applications. Consequently, signal and spectrum analyzers with an internal demodulation bandwidth of up to 2 GHz are commercially available today. The R&S®FSW signal and spectrum analyzer with internal bandwidth options executes wideband measurements up to 2 GHz bandwidth with more than 60 dBc spurious free dynamic range (SFDR).

To demodulate and analyze automotive radar signals, especially in R&D labs, demodulation bandwidths of up to 5 GHz are required. For this purpose, it is possible to combine a high-performance signal and spectrum analyzer with an oscilloscope as an external A/D converter.

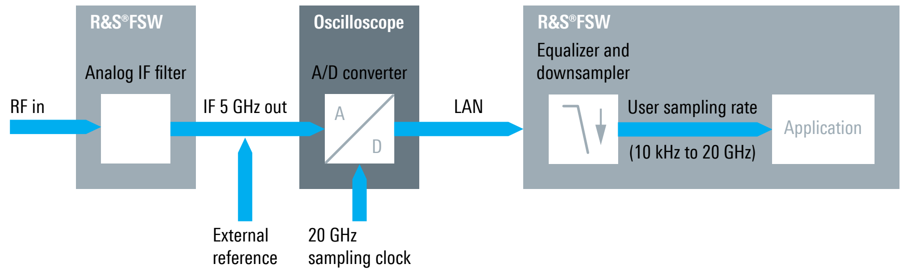
Fig. 6: The R&S®FSW85 signal and spectrum analyzer equipped with the R&S®FSW-B5000 hardware option used together with an R&S®RTO2064 oscilloscope as an external digitizer provides an equalized 5 GHz signal analysis bandwidth.

Depending on the measurement bandwidth set by the user, the analyzer downconverts the signal to an intermediate frequency of 2.8 GHz or 3.5 GHz. The oscilloscope digitizes the signal and transfers the digitized data back to the analyzer via LAN. Fig. 7 shows a block diagram of the signal processing.

The entire signal path from the spectrum analyzer's RF input to the oscilloscope's A/D converter is characterized with respect to amplitude and phase response. The digital data from the oscilloscope is mixed to the digital baseband and the measurement applications receive equalized I/Q samples.

The connection between the oscilloscope and the analyzer is completely transparent to the user. The signal analyzer fully controls the oscilloscope, transferring, processing and equalizing the digital data.

Fig. 7: Signal processing block diagram to achieve 5 GHz demodulation bandwidth with the R&S®FSW, the R&S®FSW-B5000 option and the R&S®RTO2064



The R&S®FSW downconverts the signal to an intermediate frequency of 2.8 GHz or 3.5 GHz. The R&S®RTO2064 then digitizes the signal with a sampling rate of 20 GHz and transfers it back to the R&S®FSW via LAN. Various R&S®FSW measurement applications can analyze the resulting I/Q data.

Maximum measurement time with activated 5 GHz I/Q bandwidth extension

The 5 GHz bandwidth extension makes it possible to capture ultra wide chirp sequences without missing any data. In each sweep or I/Q data acquisition, the analyzer captures a certain amount of gapless data.

The longest gapless sequence the analyzer can capture with 5 GHz bandwidth depends on the data rate that the oscilloscope processes and on the installed memory updates.

If the oscilloscope uses a sampling rate of 20 GHz and has a memory depth of 2000 Msample, the maximum record length that can be achieved for a measurement bandwidth of 5 GHz is calculated as:

$$\left((2000\ \text{Msample} \cdot 6.25\ \text{GHz})/20\ \text{GHz}\right) - 100 = 624.999900\ \text{Msample},$$

where 6.25 GHz is the sampling rate used by the analyzer for 5 GHz analysis bandwidth. The maximum measurement time can be calculated as:

$$MaxMeas\_time(s) = \frac{MaxRecordLength\_analyzer(Msample)}{Sampling\_Rate_{Analyzer}(GHz)} = \frac{624.99}{6.25} \cong 100\ \text{ms}$$

The formula indicates that an R&S®FSW equipped with the 5 GHz analysis bandwidth extension and used with an R&S®RTO2064 oscilloscope is able to capture up to 100 ms of gapless I/Q data in a single acquisition. Different measurement applications allow in-depth analysis of the captured I/Q data. The section below shows an example of wideband analysis of an FMCW chirp signal with a bandwidth close to 5 GHz at 77 GHz, similar to the signals used in automotive radar applications.

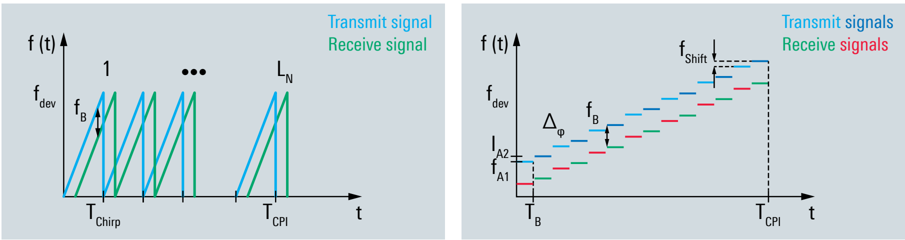
Analysis of an FMCW signal in the E band: measurement approaches and performance parameters

The most common waveforms used in automotive radar are typically chirped or hopped continuous wave (CW) signals. There is not a common waveform standard. Waveforms are specific to each radar manufacturer and belong to their intellectual property.

CW radars have low transmit power compared to pulsed radar systems. This allows the radar to be compact in size and economical. Other advantages such as zero blind range, direct measurement of Doppler frequency shift and the possibility to measure static targets make CW signals very well suited for the automotive and industrial sector.

The first automotive radars used hopped signals like MFSK. Nowadays, an increasing number of automotive radars generate frequency modulated chirp waveforms, e.g. slow LFMCW or fast FMCW waveforms.

Fig. 8: Frequency modulated continuous wave (FMCW) chirp waveforms (left) versus multiple frequency shift keying (MFSK) waveforms (right)

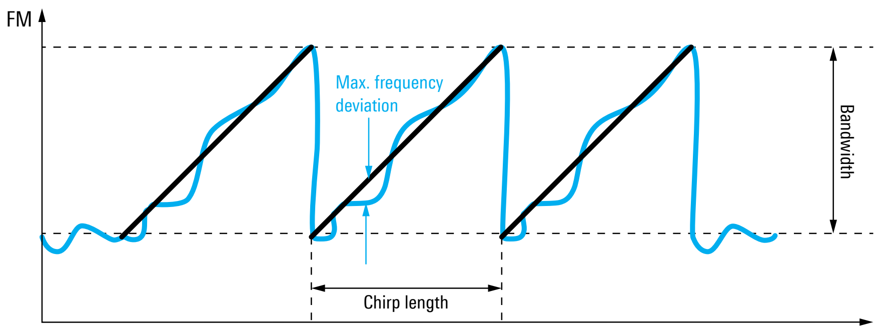


Most automotive radars use chirp sequences consisting of several very short linear frequency modulated continuous wave (LFMCW) chirps, each with a duration of T_{Chirp} transmitted in a block of length T_{CPI}.

Parameters such as signal bandwidth, chirp duration and chirp rate have a direct influence on the radar's distance and velocity resolution.

The achieved range and radial velocity resolution also depends on the signal linearity. Unwanted effects in the radar signal will affect the estimation accuracy and radar system performance.

Fig. 9: Linearity parameters for chirped signals



For the analysis of continuous wave radar signals, a dedicated measurement application is available. It supports the analysis of chirped signals. The measurement application detects the beginning and end of individual chirps within I/Q data captured by the signal analyzer. It calculates all performance parameters within a user-defined analysis range, i.e. a measurement bandwidth and acquisition time.

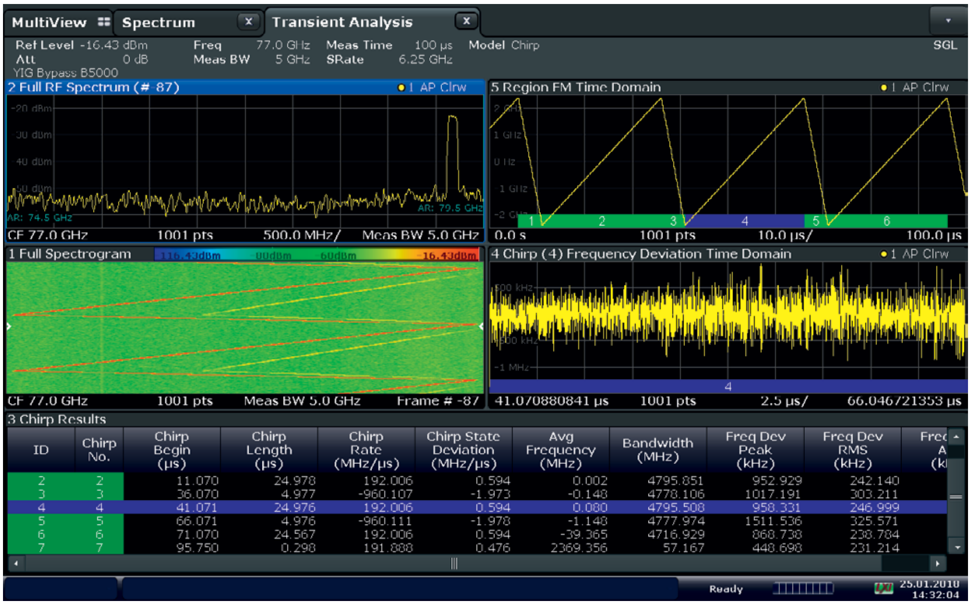


Fig. 10: R&S®FSW-K60c transient measurement application

The figure above shows a screenshot of the chirp measurement application:

- The "Full Spectrogram" graph shows the full I/Q capture buffer in the time (vertically upwards) and frequency (horizontal) domain. The color indicates the power level.
- In this example, the measurement time has been set to 100 µs; six frequency chirps with a bandwidth close to 5 GHz have been captured.
- The "Full RF Spectrum" graph represents an FFT of a part (frame) of the capture buffer. Here it is the last frame – the upper line in the spectrogram. The main carrier is visible.
- The "Region FM Time Domain" displays the frequency modulation (FM) of the signal versus time; a blue or green color bar underlines the 6 detected chirps. A video filter of 1 % of the demodulation bandwidth (i.e. 50 MHz) filters out unwanted signals and noise before the peak detector.
- The "Chirp Frequency Deviation Time Domain" displays the frequency error of the demodulated FM signal versus time for one of the detected chirps.
- The "Chirp Results" table displays all parameters of interest for all detected chirps.
- In the example, the application detects the chirps automatically and calculates the frequency deviation assuming a best fit linear chirp as a reference.

The next section explains chirp detection and linearity measurements in detail.

Chirp detection

By default, the analysis application automatically detects the so-called chirp states: the different nominal chirp rates in MHz/µs and a tolerance span to compensate for settling effects. As long as the chirp rate deviation remains within the tolerance above or below the nominal frequency, the chirp is detected.

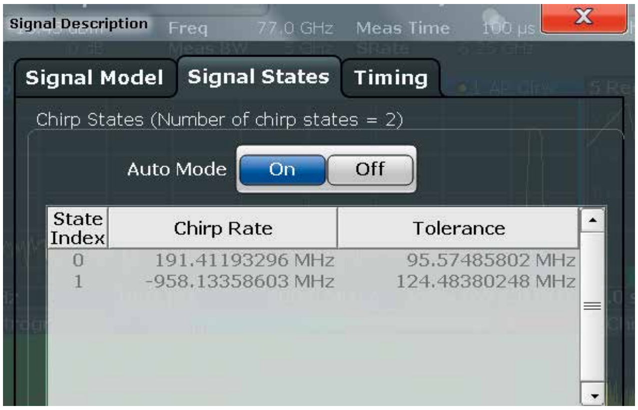


Fig. 11: Signal description table in the R&S®FSW-K60C application, chirps are detected automatically (auto mode: on)

In the default automatic mode, the application calculates the nominal chirp rate and the tolerance from the chirp rate time domain trace (Fig. 12). The application calculates the distribution of the measured chirp rate and detects those parts of the signal with a relatively constant chirp rate.

The nominal chirp rates in the signal description table are those chirp rates that occur more often. The tolerance value increases if the signal noise increases and the chirp rate is not constant.

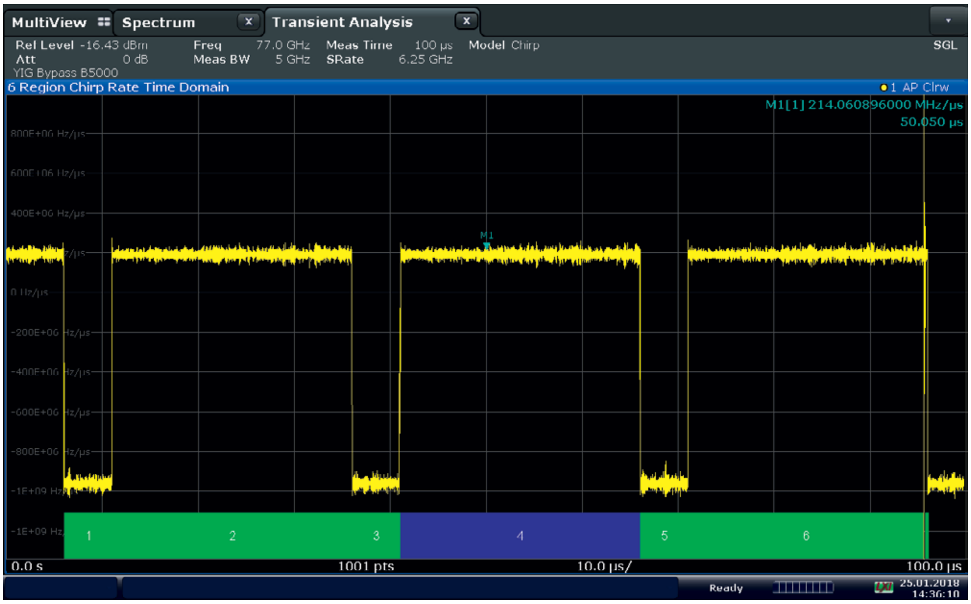


Fig. 12: Chirp rate measurement in the time domain used as a base for chirp detection

For an initial overview of the signal, the default automatic detection is usually sufficient. If you know the signal's nominal frequency or chirp rate values, you can enter those manually in the signal states table (Fig. 11) and turn auto mode off. The application will then detect the chirps that meet the user-defined chirp rate and tolerance values.

Chirp linearity measurement: best fit versus user defined

For radar systems using chirped frequency modulated (FM) signals, FM linearity is an important measurement. The FM and the frequency deviation in time domain measurements are key when measuring linearity.

The frequency deviation in the time domain is calculated with respect to a certain FM reference signal.

By default, the FM reference signal is calculated directly from the average measured chirp rate (Fig. 12). Any deviation from the measured average chirp state is compensated for.

The default setting is recommended if you want to see the smallest deviation from a best fit of the model parameters In this case, the compensate chirp state deviation checkbox is activated (Fig. 13).

Fig. 14 shows an example of a linearity measurement using the best fit approach focusing on one chirp. A marker has been set to highlight the peak frequency deviation in the time domain.

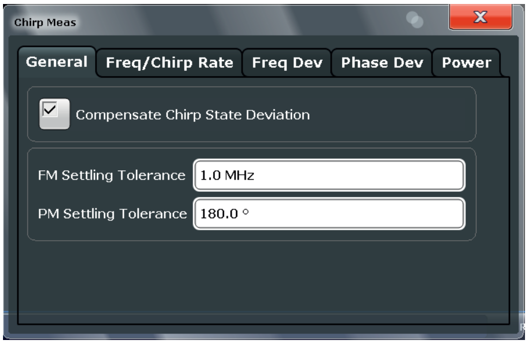


Fig. 13: By default, the measured chirp rate is used to perform the chirp linearity measurement and any deviation to the average chirp state is compensated for.

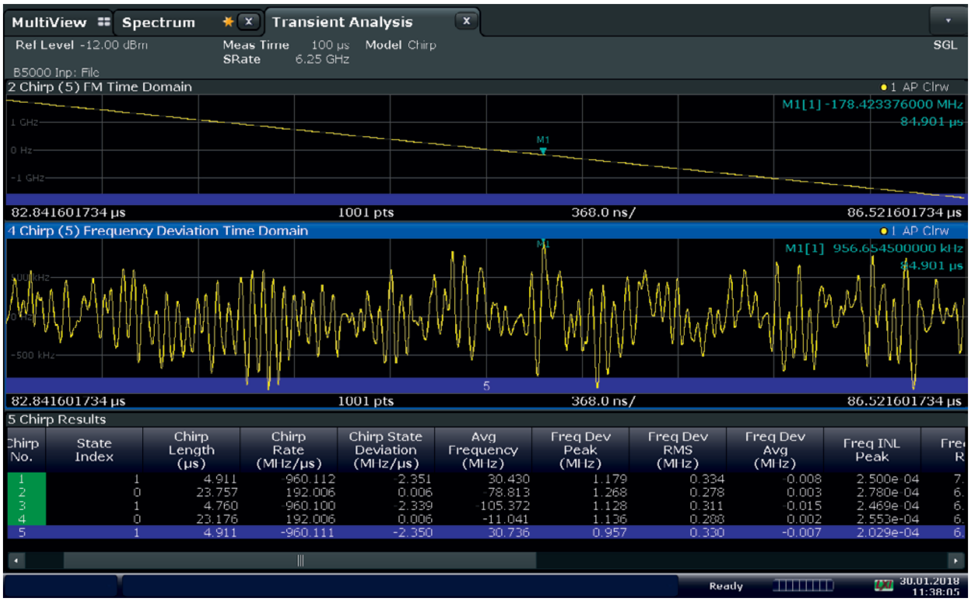


Fig. 14: Example linearity measurement with best fit measurement approach. Focus on chirp 5; FM time domain and frequency deviation time domain parameters

In practice, it is often required to measure the FM deviation trace with respect to a known, user-defined nominal chirp rate in order to verify that the radar signal meets the specified chirp rate and tolerance.

In this case, you can turn auto mode off and enter the specified chirp rate and tolerance values in the signal description table (Fig. 11) and measure the deviation between the measured and specified values. For this measurement, the user must turn off auto mode and deactivate the "Compensate Chirp State Deviation" checkbox.

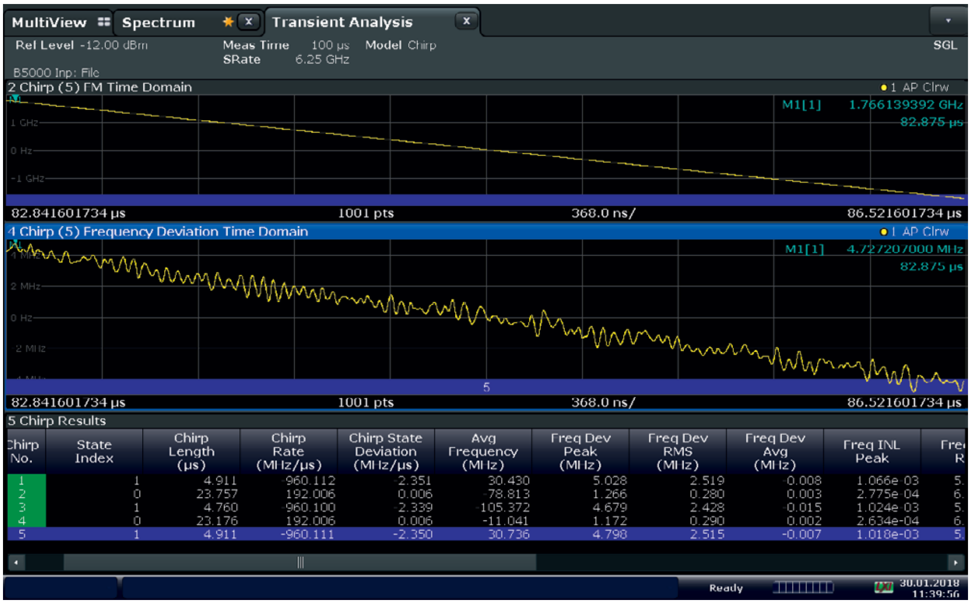


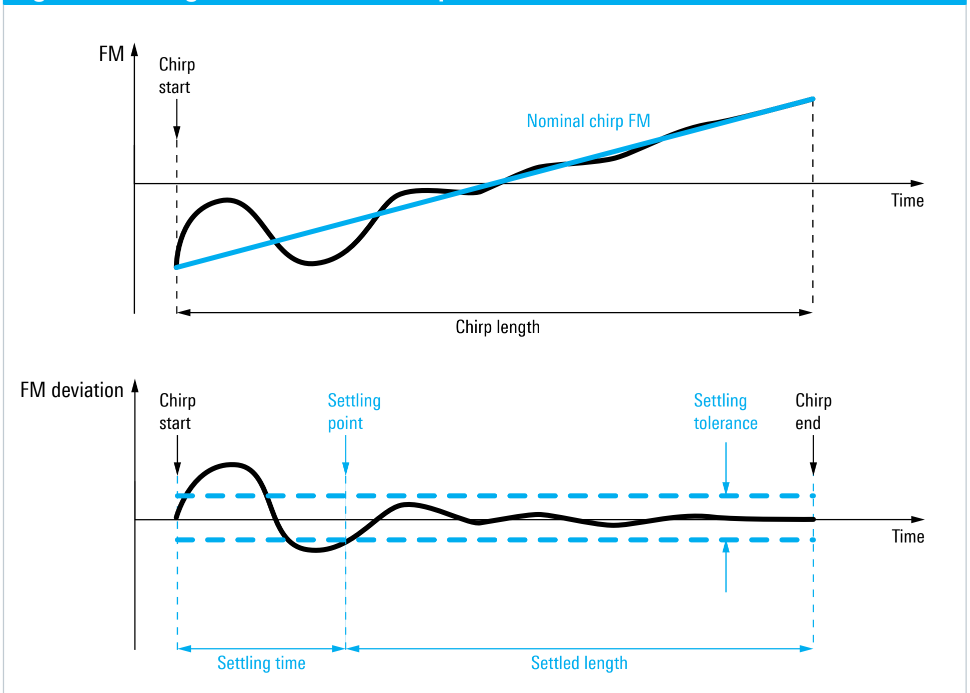
Fig. 15: Frequency deviation calculated using the nominal chirp rate values in the signal description table as a reference instead of the measured average chirp rate (best fit)

Measurement of chirp settling time

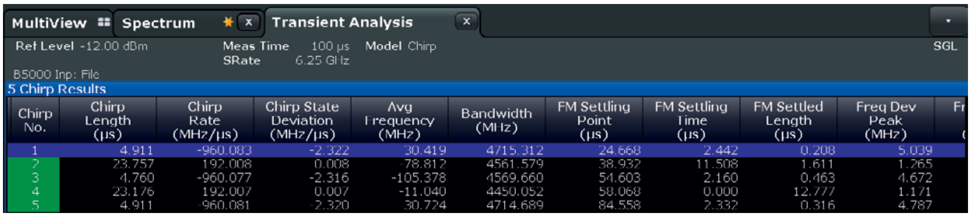
In order to more accurately calculate frequency, phase or power results for chirped signals, you can define a measurement range and take only a certain portion of the chirp into consideration, to eliminate settling effects for instance.

It is also important to measure the chirp settling time, which is the time it takes the FM signal to remain within a specified tolerance around the nominal frequency. Settling parameters such as chirp settling time, settling point and settled length are calculated from the FM deviation taking into consideration the user-defined FM settling tolerance as shown in Fig. 16.

Fig. 16: Settling time measurement parameters



The screenshot below shows the settling time and settling point measurement results for the example signal in Fig. 10, where the FM settling tolerance has been set to 1 MHz around the nominal frequency.



MultiView | Spectrum | Transient Analysis

Ref Level -12.00 dBm | Meas Time 100 µs | SRate 6.25 GHz | Model Chirp | SGL

B5000 Inp: File

5 Chirp Results

Chirp No.	Chirp Length (µs)	Chirp Rate (MHz/µs)	Chirp State Deviation (MHz/µs)	Avg Frequency (MHz)	Bandwidth (MHz)	FM Settling Point (µs)	FM Settling Time (µs)	FM Settled Length (µs)	Freq Dev Peak (MHz)
1	4.911	-960.083	-2.322	30.419	4715.312	24.668	2.442	0.208	5.039
2	23.757	192.008	0.008	-78.812	4561.579	38.932	11.508	1.611	1.265
3	4.760	-960.077	-2.316	-105.378	4569.660	54.603	2.160	0.463	4.672
4	23.176	192.007	0.007	-11.040	4450.052	58.068	0.000	12.777	1.171
5	4.911	-960.081	-2.320	30.724	4714.689	84.558	2.332	0.316	4.787

Fig. 17: Measurement results for 1 MHz FM settling tolerance

Summary

Rohde & Schwarz offers a flexible, fully integrated and user-friendly solution to overcome the challenges of analyzing ultra wide automotive radar signals in the E band. The R&S®FSW85 makes it possible to measure a gapless spectrum from 2 Hz to 85 GHz or 90 GHz with a single instrument. A built-in YIG filter ensures an image-free spectrum up to 85 GHz.

The R&S®FSW-B5000 5 GHz bandwidth extension combined with an R&S®RTO oscilloscope as an external digitizer offers an equalized and fully characterized signal path. The signal analyzer controls the oscilloscope so that the complete operation is performed through the R&S®FSW user interface.

The transient analysis application running on the R&S®FSW provides flexible and in-depth analysis of signals transmitted by radar chips, sensors and components. It measures the main signal parameters such as signal linearity either automatically or manually depending on the user's needs.

References

Number	Reference
[1]	C. Rauscher, Fundamentals of Spectrum Analysis, Rohde & Schwarz, Munich, ISBN 978-3-939837-01-5
[2]	Rohde & Schwarz, S. Heuel, "Radar Waveforms for A&D and Automotive Radar", White Paper
[3]	Rohde & Schwarz, S. Heuel, "Automated Measurements of 77 GHz FMCW Radar Signals", Application Note
[4]	R&S®FSW IQ Analyzer User Manual, Rohde & Schwarz, Munich
[5]	R&S®FSW-K60 Transient Measurements User Manual, Rohde & Schwarz, Munich

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, monitoring and network testing. Founded more than 80 years ago, the independent company which is headquartered in Munich, Germany, has an extensive sales and service network with locations in more than 70 countries.

www.rohde-schwarz.com

Regional contact

- Europe, Africa, Middle East | +49 89 4129 12345
  customersupport@rohde-schwarz.com
- North America | 1 888 TEST RSA (1 888 837 87 72)
  customer.support@rsa.rohde-schwarz.com
- Latin America | +1 410 910 79 88
  customersupport.la@rohde-schwarz.com
- Asia Pacific | +65 65 13 04 88
  customersupport.asia@rohde-schwarz.com
- China | +86 800 810 82 28 | +86 400 650 58 96
  customersupport.china@rohde-schwarz.com

R&S® is a registered trademark of Rohde & Schwarz GmbH & Co. KG
Trade names are trademarks of the owners

PD 5216.1292.52 | Version 01.00 | November 2018 (sk)
White paper | Advanced methods for analyzing ultra wide automotive radar signals
Data without tolerance limits is not binding | Subject to change

© 2018 Rohde & Schwarz GmbH & Co. KG | 81671 Munich, Germany

5216129252

5216.1292.52 01.00 PDP 1 en

Electro Rent

ROHDE&SCHWARZ

Development and Test of New Automotive Radar Technologies

Learn About Testing Technologies for Increasing Bandwidth for Automotive Radar

DOWNLOAD NOW

electrorent.com • 800.553.2255 • sales.na@electrorent.com